2016

Digital textile printing: colorfastness of reactive inks versus pigment inks

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Digital textile printing: Colorfastness of reactive inks versus pigment inks

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Apparel, Merchandising, & Design

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Iowa State University

Ames, Iowa

2016

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

First and foremost, I want to express my sincere gratitude towards my major professor, Dr. Eulanda Sanders, for her guidance, patience, and constant encouragement each and every day. Thank you for taking this journey along with me and for helping me every step along the way.

Thank you to Dr. Chunhui Xiang, my co-advisor, who introduced me to the entire textile testing equipment and procedures. Thank you for being so flexible and willing to help me on such short notices. Thank you to Professor Cindy Gould for your endless amounts of encouragement, editing, and for always lifting my spirits up.

Thank you to my family and friends for all of their encouragement and support. Thank you for allowing me to pursue my dreams; I could not have done any of this without you.

ABSTRACT

Digital textile printing is over-taking the printing industry with eco-friendly processes and ability to produce short runs. With its rapid growth, there is a constant need to reproduce consistent colors throughout different print runs and crucial for these colors to perform well and up hold under certain conditions. The purpose of this study was to research the colorfastness digitally printed reactive and pigment inks printed on cotton fabrics. Fabric swatches printed using the reactive and pigment inks were tested according to the AATCC standards for laundering, crocking, light, and perspiration.

The digital textile printing industry has slowly started transitioning from printing with reactive inks to primarily pigment inks. Printing with pigment inks is more cost effective and cheaper than reactive inks and has had a large impact on the printing industry. While reactive inks are printed on natural fibers, such as cotton and silk pigment inks, have the ability to be printed on natural and synthetic fibers.

To test the textiles, a Mimaki TX2 1600 digital textile printer was used to print the reactive ink samples while an outside printing company was used to print the pigment ink samples. One hundred and twenty-eight test samples sizes 2"x6"printed with a red, blue, and green geometric pattern were tested. Both the pigment and reactive samples were testing according to the AATCC standards for colorfastness to laundering, crocking, light, and perspiration.

Using a spectrophotometer, the samples were tested and the CIELAB color and ΔE* color change were obtained. The samples were also tested using the AATCC gray scale and 9-step chromatic transference scale. Using the Wilcoxin rank sum test the pigment and reactive samples were compared to record any statistical significance in color change.

The results revealed that the colors printed using pigment inks perform better than reactive inks. Pigment inks experienced much less color loss than the reactive inks in laundering, crocking, and perspiration. Light had little to no impact on the color of both the reactive and pigment samples. Evaluating the reactive and pigments ink types and their colorfastness benefits academia and the industry. This research provides recommendations of how these ink types may be best suited for certain types of apparel and products.

CHAPTER 1. INTRODUCTION

With evolving popularity, digital textile printing has become an innovative technology for coloration of textiles. It is the process of printing any type of design or images on textiles with the use of technologies (Bae, 2007). The words digital textile printing (DTP) seems like a relatively simple process; however, it is not. The process consists of utilizing highly specialized systems and techniques that make the printing process anything but simple. The quality of the printed end product depends on the hardware, software, ink chemistry, chemical pre-treatments, and post-treatment processes (King, 2009). DTP has the capabilities of providing short-run prints and a quick turnover rate, resulting in a drastic impact on the mass-customization market.

Digital textile printing, in the last decade, has made its way into the mass customization market; as well as slowly replacing original screen-printing processes (Li, 2003). It is essential that the colors and patterns in a textile design be identically replicated during each textile print run, because color reproduction should be consistent and reproducible. For instance, when a consumer orders five yards of a red, blue, and green plaid fabric, it is unacceptable for them to receive fabric that is red-orange, violet, and blue-green. Therefore, research is needed to provide information that will help textile designers, producers, and academics to prevent color inconsistencies in digital printing.

Inconsistent color reproducibility in digital textile printing can result from a number of different factors. The digital textile printer itself must be consistently cleaned, calibrated, and profiled the same way for each print run (Loser & Tobler, 2006). All print heads should function in pristine condition and be properly running. Figure 1.1 shows a test draw before cleaning, with nozzles and heads clogged. Figure 1.2 defines "pristine condition," meaning all print heads and nozzles are working properly and to the best of their abilities.

Figure 1.1 Before Cleaning

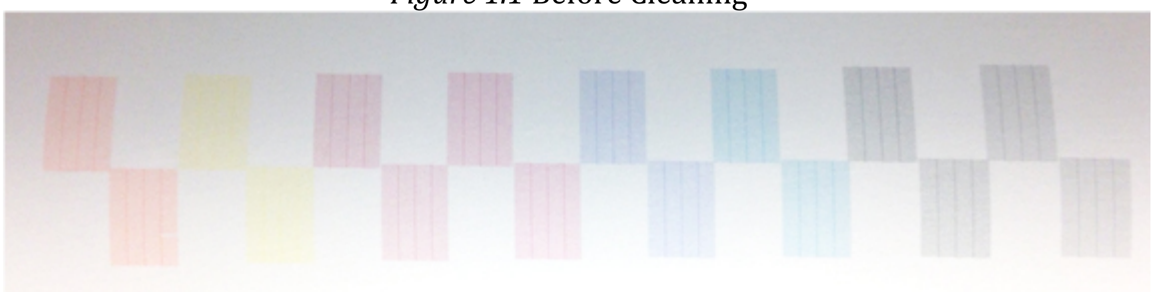


Figure 1.2 After Cleaning

The humidity in the room can drastically change the colors the inks produces. This is because having too high or too low of humidity can affect the overall ink flow (P. Aster, personal communication, February 22, 2016). Characteristics of the ink also has an effect on the color, therefore very low ink of one color or installing new inks sets prior to printing may slightly alter the outcome of the print (Ross, 2001). While many institutions still use reactive ink printers, many are moving in the direction of the industry, which are pigment inks (P. Aster, personal communication, February 22, 2016). Other variables such as the fabric pre-treatment, steaming, and the post-treatment processes need to be taken into consideration as well. Various researchers have evaluated the colorfastness of types of dyes (Blackburn, et al., 2002; Haar, et al., 2013; Sarkar, et al., 2003) and while there have been many studies conducted on the chemistry of inks, types of printers, and chemical pre-treatments, the colorfastness of inks used for digital textile printing have been understudied.

The purpose of this study was to evaluate the colorfastness of digitally printed fabrics printed with both reactive and pigment inks. With the industry switching from reactive inks to primarily pigment inks, both ink sets will be researched to determine the performance of each. Samples consisting of red, blue, and green will be printed on cotton fabric using reactive inks and pigment inks. Using the AATCC standards, both the reactive and pigment samples will be tested for colorfastness by laundering, light, crocking, and perspiration standards.

Research Questions

The following research questions were developed to address the purpose of this research in regards to selected cotton woven and knit fabrics:

1. What are the colorfastness differences for fiber reactive inks versus pigment inks printed on cotton sateen and cotton twill in regards to AATCC test standards for: (a) laundering, (b) crocking, (c) light, and (d) perspiration?
2. What are the initial color value differences between specific cotton fiber fabrics printed with fiber reactive inks versus pigment inks, when tested under AATCC test standards for: (a) laundering, (b) crocking, (c) light, and (d) perspiration?

Objectives

The following objectives have been identified to answer the previous research questions:

1. Select 5 different cotton fabrics to be printed with pigment inks.
2. Select 5 different cotton fabrics to be printed with reactive inks.
3. Digitally print 2” x 6” fabric swatches consisting of a red, blue, and green print design using reactive inks.
4. Order digitally printed swatches from an outside textile printing company to be printed using pigment inks.
5. Conduct the following tests according to the AATCC standards on all samples:
    a. Laundering
    b. Crocking
    c. Light
    d. Perspiration
6. Use a Cary UV-Vis 300 spectrophotometer to obtain CIELAB color and ΔE^* color change.
7. Obtain ratings using the AATCC gray scale and 9-step chromatic transference scale.
8. Use the Wilcoxon rank sum test to determine statistical significance of color loss.

Scope

Textile Printer

A Mimaki Tx2 1600 printer was used to digitally print the textiles. According to Ryall, the majority of academic institutions in 2009 print with the Mimaki Tx2 1600 printers because this particular design of printer offers flexibility. The flexibility is more important for institutions than speed of printing because the types of student projects vary immensely and requires more of an independent approach (2010).

The print heads went through an extensive cleaning both by hand and by machine before samples are printed. The cleaning process consists of using a cleaning solution and distilled water to remove all crusted, leftover inks from on and around the print heads. The digital files were sent from the computer to the Mimaki printer from the Wasatch program through RIP software. All swatches were printed on the same day under the same conditions to ensure accurate readings.

Inks

The thickeners in the dye paste of reactive dyes are one reason why they are used in conventional printing (Tyler, 2005). Reactive dyes require a pre-treatment on fabrics before printing can occur. Reactive dyes are intended for natural fibers and produce vivid and durable colors that uphold over time and also have excellent wash fastness. The wash fastness of the natural fibers is created from the chemical bond that happens between the dyes and the substrates in the reactive dyes. (Bae, 2007). Reactive dyes do not give off the widest range of color yield and work best mainly on natural fibers. Reactive dyes are used in the digital apparel textile studio at Iowa State University because they are the most readily available and work best on silks and cottons; which are the most popularly used fabrics.

Pigment inks are mainly used in the digital printing industry. Pigment inks print well on synthetic materials such as polyester and nylon (Clark, 2007). The ink sits on top of the fabric instead of being absorbed into the fabric because the ink is applied with a resin binder (Li, 2003). A simple heat treatment such as an oven or a heat press is all that is required to cure the pigment inks, making the process cheaper than reactive inks. This is the main principal for the dominance of pigment printing in the ink-jet printing industry (Li, 2003).

Fabric Selection

Cotton fabrics were purposely chosen for this experiment since natural fibers absorb inks better than synthetics. When different types of fabrics are printed with the same textile design, under the same conditions, and using the same inks, the final color outcome may still slightly differ. This can result from fiber content, fabric type and weave structure. This is why the cotton fabrics, with different weave structures, were selected for this study. The reason for the differentiation is the structure of the fiber. The structure of the fiber is composed of the length, diameter, cross-sectional shape, and longitudinal shape. According to Bae (2007), long plant fibers tend to produce a fabric with brighter color appearance and higher overall luster. Fabrics consisting of courser yarns tend to have a less smooth surface and more texture, resulting in a darker color value (Bae, 2007).

With the reactive dyes, the cellulose of the natural fibers reacts with the dyes to form a covalent chemical bond (Ervine S, Seimensmeyer K, Seigel B, 2000). Used for many years because of their water solubility, reactive inks have been mainly used because of their ease to form the suitable ink formulation (Ervine et al., 2000). The fabric used for the reactive ink part of this study will go through a pre-treatment process and will also be paper backed. The reason for paper backing the fabric is to add stability as the fabric is making its way up and under the print heads. Without the paper backing the fabric will slide, make the print inconsistent, and will not be on grain. Pigment inks print well on cotton fabrics as well and require no pre-treatment of the fabric.

Assumptions

The assumptions were made that the:

1. Pigment samples were printed by an outside textile printing company using pigment inks.
2. Findings from the gray scale test are valid based on one person's visual perception.
3. Iowa State University's digital textile printer was in pristine condition and printing its best quality.

Limitations

A few limitations arose during the research:

1. This experimental research was completed using a Mimaki TX2 1600 textile printer; other brands and models of textile printers may produce different results.

2. The samples ordered from an outside textile printing company were printed by their employees. I am unaware if a pre-treatment occurs or what the heat setting, post-treatment process is for the digitally printed fabrics.
3. The textiles printed with reactive dyes at Iowa State were printed in CIELAB color mode using reactive inks. All of the fabric was pre-treated by an outside textile printing company before arrival at Iowa State University. The textiles were steamed for the same amount of time using the same industrial bullet steamer. Depending on the water level and steamer condition, results may vary.
4. All post-printing washing of the reactive printed textiles was completed with the Atlas Launder-Ometer following the ATCC standards. The home washing test was done using a Maytag washer and dryer. The specific results concluded from this study resulted from using these particular pieces of equipment; therefore, using other types of equipment may alter the end results.

Definitions

Acid dyes	Type of dye used for digital textile printing mainly on protein fibers, tending to have good light fastness and produce bright colors (Tyler, 2005).
Back staining	a defect from digital textile printing where the textile print runs and is visible from the backside of the fabric (Ryall, 2010).
CIE	Represents the limits of human vision, XYZ or XYY coordinates (Dawson, 2006).

Cleaning	As relates to the printer
Colorfastness	The transfer of color from any textile to adjacent materials or the resistance of a textile to change in any of its color characteristics due to exposure to the environment during testing, storage, or overall use of the textile (AATCC, 2015).
Colorfastness to light	The change in color of a material as a result of exposure to either sunlight or artificial light (AATCC, 2015).
Color reproduction	The color must be a near perfect match for all print runs (Ervine et al., 2000).
Continuous ink jet printing	An ink jet printing method using a constant stream of ink (Ryall, 2010).
Crocking	The transfer of color from the surface of one textile to another material surface usually caused by rubbing (AATCC, 2015).
Disperse dyes	A type of ink used for digital textile printing on polyester fabrics where the dye has been very finely milled into a form that can be dispersed into water since polyester is highly hydrophobic (Tyler 2005).
Drop on demand printing	A type of ink jet printing where each drop of ink can be specifically controlled (Dehghani, Jahanshah, Borman, Dennis, Wang, 2004).
Gamut	Range of colors capable of being produced by a particular output device (Ryall, 2010).
Laundering	Process of washing textiles intended to remove soils and stains used with detergent solution and is a cycle of agitation, rinsing, extracting, and drying (AATCC, 2015).
Perspiration	Sweat glands secrete a saline fluid from the body (AATCC, 2015).
Piezoelectric	A type of ink jet printing where an electric current is sent to the piezo crystal at the back of the ink reservoir (Ryall, 2010).

Pigment dyes	A type of ink used for digital textile printing where no pre-treatment and a short post-treatment is required (Ryall, 2010).
Print heads	The part of the printer that transfers in onto fabric. Print heads contain nozzles that eject ink. (Ryall, 2010).
Profiling	Creating a color gamut from a printable range of colors attainable for that certain printer (P. Aste, personal communication, February 22, 2016).
Properly running	Printing with all print heads and nozzles aligned and running properly. During a test draw there are no missing or unaligned nozzles (P. Aste, personal communication, February 22, 2016).
Reactive dyes	A type of ink used in digital textile printing that has good fastness properties due to the bonding that occurs during dyeing (Ervine, 2000).
Rotary screen-printing	A type of screen-printing using revolving cylindrical screens with the squeegee located between the cylinder (Ryall, 2010).
Spectrophotometer	A device used for measuring the intensity of light and color (Bae, 2007).

CHAPTER 2. REVIEW OF LITERATURE

The Evolution of Digital Textile Printing

Around the mid-1900s digital laser versions of electro photography was transferred onto fabric and clothing making it one of the first uses of digital technology (Cahill, 2006). Banners, billboards, and building wraps were all some of the first items digitally printed before clothing, with the very first and most popular item being carpet (Cahill, 2006). Before digital textile printing (DTP), designers who wanted to produce textile design art were limited to a few options. Designers could either hand silk-screen print, which is a timely and labor-intensive process, or they could hope that a fabric company would pick their textile design and rotary screen-print it on large runs (Lui, 2008). DTP enables designers to incorporate graphic design elements, photographs, artworks, and almost any type of media into textile prints quickly and easily (Lui, 2008). Using these technologies can continuously open up an expanding range of endless creative possibilities and generate more complex design ideas and decision points for designers (Campbell & Parsons, 2005). DTP enables the printing of short-runs, resulting in shorter lead times so this new printing technology is slowly taking the place of basic screen-printing.

Impact of Digital Textile Printing on the Environment

Along with being able to produce short-run fabric and long-run fabric in a short amount of time, DTP is also environmentally friendly because its wastewater production is relatively small (Chang, Lee, Choe, 2008). Other DTP benefits are that it requires no setting or washing of tools such as screens, the post-treatment process saves from the runoff of inks into our sewer systems, and all work can be printed to order, printing only the exact amount the customer needs (Dehghani et al., 2004). DTP is a dry printing process working similarly to a desktop inkjet printer; while conventional printing is a wet process consuming huge amounts of dyes and water (Chang et al., 2008). Engineered garments have little to no ink waste due to printing only the design in the pattern pieces necessary and leaving the rest of the fabric white. With this process only the exact amount of inks and dyes are used in the creation of the garment and there is no left over printed fabric. According to Parsons and Campbell (2005), "The digital textile printing design potentials are perfectly suited for the creation of unique and innovate mass customizable garments" (p. 9).

Digital Printing Hardware

Textiles are digitally printed using the ink jet print system. There are two types of ink jet printing: (a) Continuous and (b) Drop on Demand. The most common type of ink jet printing is Drop on Demand (Ryall, 2010). By applying a constant pressure, ink is squirted through a nozzle at a constant speed in continuous ink jet printing (Kobayashi, 2006). After leaving the nozzle the ink breaks up and forms droplets, which are dispersed onto the fabric drop by drop. It is called Continuous ink jet printing because the ink jets are being ejected continuously at all times (Cahill, 2006). Drop on demand (DOD) is generated by printing software that instructs the print head to either drop ink or to not drop ink on the fabric surface (Bae, 2007). DOD offers two types of printing, piezoelectric and thermal. During thermal ink jet printing, the dye inside the print head is heated up rapidly, causing pressure to create a bubble that then bursts with dye (Ryall, 2010, Gregory, 2003).

Piezoelectric is the most popular and most favored type of printing. During piezoelectric printing, an electric current is sent to the back of the ink reservoir, allowing for more freedom of the ink drop size and shape (Ryall, 2010). Especially important for printing photographs, piezoelectric ink jet printing can produce higher resolution prints in a shorter amount of time.

The digital textile printer used at Iowa State University is the Mimaki TX2 1600 with Epson print heads using piezoelectric ink jet printing. The Mimaki printer can print up to speeds of 28.4 m2/h with speeds increasing by adding new print heads with increased number of nozzles or having more print heads run with the same colors (Ryall, 2010). Input and output are communicated through a printing device RIP (Raster Image Processor) software that delivers the textile design from the computer to the printer (Ryall, 2010).

Reactive dyes are the most common dyes used at academic institutions. They are most commonly used on cotton and cotton blends, which makes up about 25% of the entire textile printing market (Chen & Zha o, 2003). Reactive dyes are used at Iowa State because of their flexibility. Reactive inks work best on cottons and other cellulosic fibers. They are called reactive dyes because covalent bonds form when the dyes react with the cellulose (Ervine et al., 2000). Reactive dyes require a steam heat fixation and a pre alkali treatment to the fabric in order to achieve a full chemical reaction (Ervine et al., 2000). Besides reactive dyes, there are three other dyes that can be used with the Mimaki printer -- acids, disperse, and pigment dyes (Ryall, 2010).

Acid, disperse, and reactive inks were initially the only ink developments, before pigment inks, that were primarily used for digital textile printing Fu, 2006). The issue with printing with acid, disperse, and reactive dyes is that the pre and post-treatment process somewhat defeats the purpose of the idea of instantaneous customization, since the fabrics have to be pre-treated and steamed and washed (Fu, 2006).

Acid dyes are used mainly on wools, silks, and polyamide fibers (Ervine et al., 2000). Acid dyes are used to print some of the most luxurious silks because of their bright, vivid, colors and good light fastness. The issue with acid dyes are that under alkaline conditions the iconic bond can actually be reversed so further care is needed for the fabric (Tyler, 2005).

Before pigment inks, disperse inks were initially used to print on polyester and nylon. Disperse dyes are only partially soluble and is dispersed into water (Tyler, 2005). Polyester is a hydrophobic fiber, which is why reactive and acid inks do not perform well with polyester. Disperse dyes are not water-soluble and therefore are able to form bonds with the fibers in polyester (Tyler, 2005).

Pigment dyes are starting to dominate the digital textile printing industry, replacing reactive inks. Pigment printing now accounts for over half of all digitally printed textiles (Ervine et al., 2000). The required process for pigment inks is much simpler because of its chemistry types compared to other inks (King, 2009). With the printing and post-process treatment being simpler it also makes printing with pigment inks cheaper. As of 2006, digital printing using pigment inks had occupied more than 50% of the printed textile market (Fu, 2006). Pigment dyes are substrate independent, meaning they can be used for printing a wide variety of fabrics and fiber blends (Ross, 2001). In pigment printing the resin binder is used to hold the ink colorants to the top of the fabric (Li, 2003). Pigmented ink formulation includes pigment dispersion, a polymeric binder for image durability, water, a co-solvent, surfactant, humectants, antifoaming agent, viscosity control, a penetrant, and a biocide (Fu, 2006). The advantage of pigment inks is that they can be applied to many different substrates and there are multiple application routes that can be taken (Ervine et al., 2000). With pigment inks it is now possible to apply color to all textiles with a relatively simple process (Ervine et al., 2000). Pigment dyes do not require a steaming and washing process but a simple dry heat process. Table 2.1 breaks down the dye type, fiber, and the pre and post treatments required according to Ross, 2001 & Fu, 2006.

Table 2.1. *Digital textile printing inks*

Ink Type	Fibers Compatible	Pre-Treatment Required	Post-Treatment Required
Acid Dyes	Silk, nylon, wool	Acid donor	Steam and wash
Disperse Dyes	Polyester	Thickener	High-temperature steam and wash/ Heat Fixation
Reactive Dyes	Cotton, natural fibers	Alkali	Steam and wash
Pigment Dyes	Cotton, polyester, poly-blends	Not required	Dry heat

Pre and Post Treatment of Digital Prints

Fabrics used in reactive, acid, and disperse DTP are chemically pre-treated to allow for maximum dye intake. Acid dyes are pre-treated with acid donor disperse dyes use a thickener, and reactive dyes use alkali (Fu, 2006). Pigment inks do not require a pre-treatment to the fabric, since the ink sits on the surface of the fabric and does not actually get absorbed into the fibers. Digital printing inks have a low viscosity; it was designed to allow flow through the print head (Tyler, 2005). The low viscosity creates problems because when the ink reaches the textile substrates, the fluid moves away from the fabric by wicking (Tyler, 2005). By pre-treating the fabric extra "padding" is added to the surface to absorb the inks and to prevent wicking (Tyler, 2005). Pre-treatment maximizes the clarity of the image, produces a quick drying time, as well as helps control the size of the ink drops released onto the fabric. Color migration and bleeding can be prevented if the pre-treatment works effectively (Bae, 2007). The amount of ink bleeding is controlled by the size of the ink drops (Ryall, 2010). For ink-jet printing with reactive inks, cotton fabrics go through a pre-treatment process where the textiles are padded with a plain paste, containing alginate thickener, urea, and $NaHCO_3$ (Chen & Zhao, 2003). Chen & Zhao (2003), tested cationic treatment on fabric and noted that it greatly enhances the color yield of ink-jet printing both on unprepared and prepared cottons. The fabric pre-treatment maximizes the clarity of the image, produces a quick drying time as well as helping control the size of the ink drops jetted onto the fabric. In addition, fabric is often backed with paper to help with stability and improve feed through the printer. After the fabric is pre-treated it is then adhered to a paper backing.

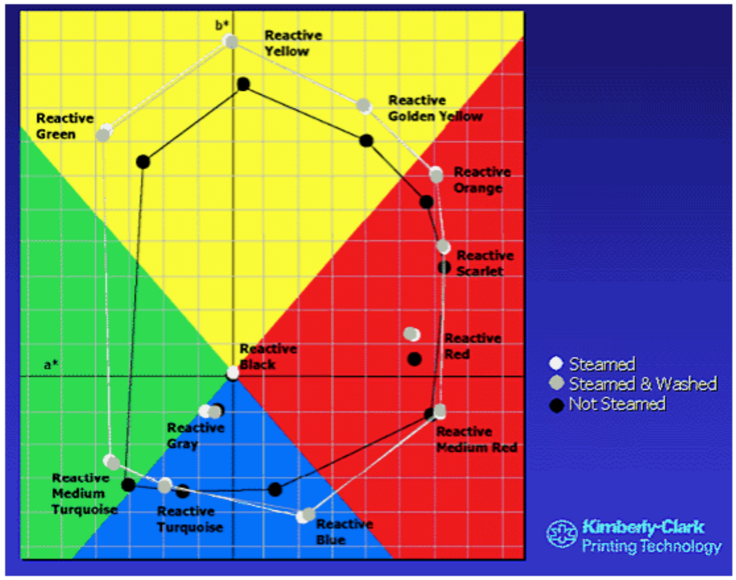
Post-Treatment Processes

The entire printing process is not complete until the fabric undergoes a post-treatment process. The fabric printed with acid, disperse, or reactive dyes is then steamed at a specific temperature to set the dyes to the fabric. During the steaming process, fibers within the fabric open up and allow the dyes to be fixed (Tyler, 2005) The steaming process intensifies the color of the inks on the textiles. Figure 2.1 is the steamer used to set reactive inks at Iowa State University.

Figure 2.1 Steamer used at Iowa State University

Pigment inks do not require a steaming process, but instead, just a simple dry heat post-treatment. Fabrics printed with pigment inks are usually fixed in either a heat press or a hot air oven as seen in Figure 2.2 (Fu, 2006). Figure 2.3 exemplifies the reactive ink gamut for steamed and not steamed fabric completed by SuSu Gordon, (2011) of Kimberly-Clark.

Figure 2.2 Heat Press used to set Pigment Inks
(http://www.digifab.com/equipment/)



12-Color Reactive Ink Set Color Gamut showing enhanced color space provided by steaming and washing.

Figure 2.3 Reactive ink color gamut (Gordon, 2011).

The washing process for reactive inks then occurs after steaming to allow for the removal of excess dyes that had not fixed in the steaming process. Washing is an important process because if done improperly, crocking, bleeding, or back staining can occur (Ryall, 2010). The fabric is ready for use after the washing process is complete.

The pre and post-treatment has an immense impact on the color of fabric. For reproducibility, the color yield must be consistent with all print runs. Color management is a system used to administer and control the communication of color from various devices (Ryall, 2010). Color management is vital to achieving reproducible results. Six to eight colors are often offered for commercial textile printing machines (Tyler, 2005). Color measurement, calibration, and profiling are the three things to control consistent color reproducibility (Bae, 2007). The most important thing to understand about a digital textile printer is what colors are attainable within the limits of specific printers and ink set combinations. It is possible for digital textile printers to be incapable of producing a particular color and no amount of color management can help solve this problem (Gordon, 2001). Limited color gamuts and the distinguishable differences in color are some of the strongest complaints about digitally printed fabric (Gordon, 2001). Increasing the number of colors in a textile printer will increase the number of colors that can be printed; simply increasing the number of print heads will not fix it (Gordon, 2001). The full potential of reactive dyes will not be visible until reacted with fabric (Gordon, 2001). Figure 2.4 exemplifies the range of shades that are often attainable when printing with reactive inks.

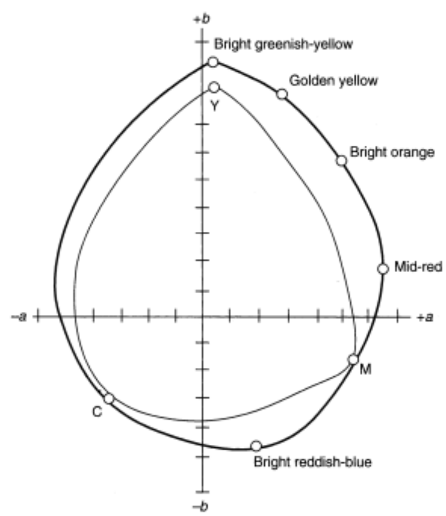


Figure 2.4 Attainable shades of colors for reactive ink dyes (Dawson, pg. 174, 2006)

Color measurement

There are three main types of color modes: RGB, CMYK, and CIELAB According to Bae, “The CIELAB color space is most widely used when dealing with surface color” (2007, p.13). All samples in this study will be printed in CIELAB color mode because of this. The CIELAB color model (CIELAB) is based on the human perception of color and describes the colors that a human with normal vision sees (Ryall, 2010). According to SuSu Gordon, “The International Commission on Lighting realized that every color the human eye perceives could be defined using three numbers L* indicates luminosity and the a* and b* are the chromaticity coordinates that indicate color directions” (2001, p.3).

Within the CIELAB color system, +a* points in the red direction, -a* is directed toward the green direction, +b* is yellow, and –b* is blue. The purity of color increases as the a* and b* move outward from the center point; the center point represents hues of gray (Gordon, 2001).

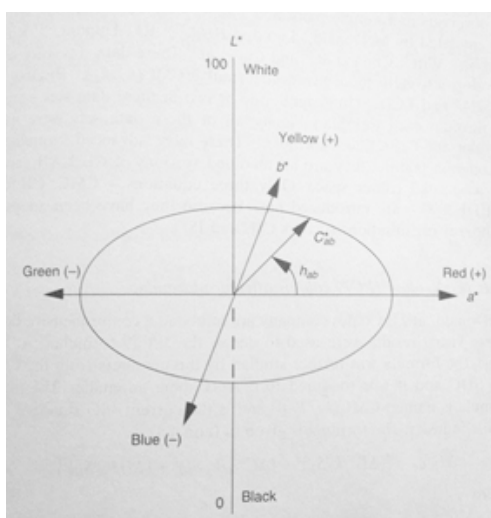


Figure 2.5 Diagram of CIELAB Color.

With CIELAB color including all perceivable color, it simply means that it exceeds CMYK and RGB color models. CIE system of color specifications is used for almost all applications of color measurements (Rigg 2006). Lab color mode is widely known to be a device independent color model and one may use Lab color mode as a color reference when trying to transform a color from one device to another. In the surface color industries CIELAB is the most widely used color model. In a particular color the values are the amounts of (X), (Y) and (Z) that are required to match a particular color under standard conditions (Rigg, 2006, pg. 33). X, Y, and Z are the tristimulus values that are calculated from measuring the reflectance values. A full specification requires the X, Y, and Z values, x, y, and Y values or CIELAB values for several different illuminates (Luo, 2006). Since the spacing of the colors in XYZ space is not uniform it can be transformed to become more uniform CIELAB color space with the following equation (Kheng, 2002):

$L^*=116\ f(Y/N_n)-16$

$A^*= 500\ \{f(X/X_n)-f(Y/Y_n)$

$B^*= 200\ \{f(Y/Y_n)-f(Z/Z_n)\}$

CMYK is a four-color printing process using three subtractive color primaries with black, cyan, magenta, and yellow (Gordon, 2001). CMYK has certain limitations of color reproducibility for bright reds, greens, and blues (Gordon, 2001). The reason why CMYK is not a highly used printable color mode is because the color gamut CMYK is able to obtain is considerably smaller than other color gamuts (Campbell, 2006). CMYK is known as a device-dependent color model resulting in it having limited access to communicating and converting color information to different output devices (Bae, 2007).

Red, green, and blue (RGB) primary colors are the colors seen on a computer screen, printer, camera, and most widely used in design processes (Tyler, 2005). RGB, along with CMYK, is a device dependent color model and also has a very limited color gamut (Bae, 2007). There are numerous colors displayed on an RGB screen than cannot be attainable using an output-printing device (Ryall, 2010). Figure 2.6 represents all of the producible colors in RGB and CMYK compared to the CIE color gamut.

(a) Visible gamut on the CIE chromaticity diagram

(b) Triangle: RBG color space
Rounded shape: CMYK color space

Figure 2.6 CIE chromaticity diagram compared to RGB and CMYK (Bae, 2007; Boscarol, 2001).

Color can be measured using many different instruments such as a spectrophotometer, depending on what specifically is being measured. Hand-held, portable instruments, which are what will be focused on for this study, range from small spectrophotometers to colorimeters. The benefits of these devices are that they generally measure a small area and the instrument is brought to the sample instead of having to bring the sample to the instrument (Clarke, 2006, pg. 49).

Spectrophotometers are instruments used to measure color. The machine measures spectral data from any additive or subtractive source (Linford, 2004). The spectrophotometer readings are the color “fingerprint” of the sample (Shen & Xin, 2006). Most spectrophotometers use diffraction grating. This is done by passing a beam of light through glass with many narrowly spaced ruled lines (Bae, 2007). Once the color is tested, it can be used to develop color standards for different devices (Ryall, 2010). By testing the color before and after the post-treatment process, one can see the immense impact the post-treatment has on the outcome of the color.

CHAPTER 3. METHOD AND PROCEDURES

Sampling

The research purpose was to evaluate the colorfastness of digitally printed textiles using pigment and reactive inks. The samples colorfastness was analyzed with a Launder-Ometer, crocking, lightfastness, and perspiration test. An experimental design process was done using five types of cotton fabrics for pigment inks and five types of cotton fabrics for reactive inks. A simple red, green, and blue geometric design was digitally printed on 2"x6" samples of cotton duck, cotton canvas, cotton twill, cotton percale, and cotton sateen using reactive inks and were printed at Iowa State University using a Mimaki TX2 1600 digital textile printer. A commercial digital printing company based in South Carolina, was used to print the pigment ink samples since Iowa State University's Mimaki TX2 1600 does not currently print pigment inks. These samples were printed on cotton lawn, heavy cotton twill, Kona® Cotton, Basic Cotton Ultra, and cotton sateen. After each test, the red, blue, and green in each sample was tested using a spectrophotometer and the LAB color was recorded as well as the color change ΔE^*. The samples were also tested using the AATCC 9 step chromatic transference scale and gray scale for evaluating color change. The Wilcoxon rank sum test was used to find the significance of colorfastness between the reactive and pigment inks. This experiment concluded with an assessment of the advantages and disadvantages of both reactive and pigment inks.

Design of the Experiment

This was an experimental design where both the pigment and reactive ink samples underwent a Launder-Ometer, lightfastness, crocking, and perspiration test. The samples were then compared to each other and the original constant sample to observe any changes. The goal of this study was to be able to find out the longevity of colors on digitally printed textiles with different ink types and which ink types performed better for colorfastness.

Pre-Treatment. All fabrics being printed with reactive inks at Iowa State University go through a pre-treatment process to allow for maximum ink intake. Digitally printed inks have a low viscosity, which allows it to flow through the print head, but creates a problem when wicking occurs once the ink hits the textile substrate. Therefore, the fabric must be pre-treated with alkali to deplete the wicking. The pre-treatment solution incorporates a thickener such as sodium alginate and alkalis to achieve fixation onto the fabric (Tyler, 2005). The fabric used for this experiment was purchased from an outside textile printing company. The fabrics are pre-treated with a solution called ProCoat.

> ProCoat fabrics are designed to be used with reactive or acid textile dyes. The treatment maintains resolution of the print and aids in the fixation and color yield of the print. ProCoat fabrics are completely washable and dry-cleanable, making them perfect for many applications including wearable and commercial textiles. ProCoat fabrics must be matched to the correct ink for the fabric type. Color is

generally post-fixed by steaming or heating.

(http://www.inkjetfabrics.com/products/fabric/procoat.php)

Fabric Selection. Cotton fabrics were selected for this experiment. To test the color fastness of reactive inks the samples were printed on cotton sateen, cotton percale, cotton duck, cotton twill, and cotton canvas. To test the color fastness of pigment inks the samples printed using pigment inks were printed on cotton lawn, Kona® Cotton, Basic Cotton Ultra, heavy cotton twill, and cotton sateen.

Color Management. The color swatches printed in this study were digitally printed in CIELAB color mode. The color swatches printed was a textile design consisting of red, blue, and green. Red, green, and blue were chosen because light reflected from the textile design sends electrical responses from the retina to the brain using the red, green, and blue cone receptors (Dawson, 2006). Most input devices such as cameras, cell phones, and scanners automatically capture images in RGB color mode (Dawson, 2006). The CIELAB color mode is the recommended and most compatible color mode used in the digital apparel textile studio at Iowa State University. CIELAB color mode creates the largest color gamut and was created ideally for textile printing (P. Aste, personal communication, February 22, 2016). When importing images or designs to the RIP software they must be changed to CIELAB color mode, therefore, it was decided to use the initial RGB true color values and translate them to CIELAB colors as seen in Table 3.1. Figure 3.1 shows the original textile design on the computer and Figure 3.2 shows the top row of pigment printed samples and bottom row of reactive printed samples.

Table 3.1. *RGB and CIELAB Initial Color Readings on a Computer Screen*

Color Mode	**Hues**								
	Red			**Green**			**Blue**		
	Red	**Green**	**Blue**	**Red**	**Green**	**Blue**	**Red**	**Green**	**Blue**
RGB	255	0	0	0	255	0	0	0	255
	L	**a**	**b**	**L**	**a**	**b**	**L**	**a**	**b**
CIELAB	54	81	70	88	-79	81	30	68	-112

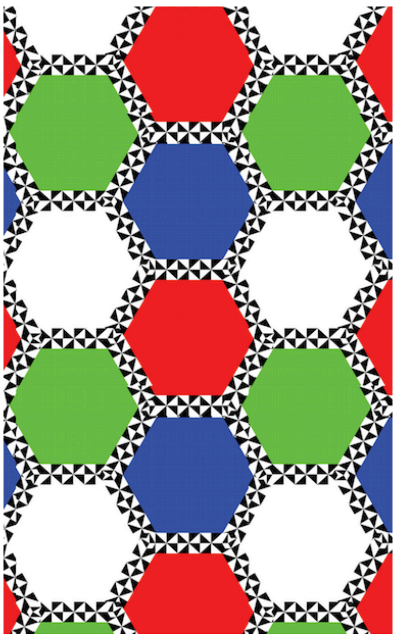


Figure 3.1 Original textile design

Figure 3.2 Original printed samples before testing

Textile Printer. The Mimaki TX2-1600 digital textile printer was used for the experiment for the reactive printed samples. This printer and ink combination is popular among academic institutions. All fabric samples were printed on the same day under the same conditions. It is unknown the exact type of printer used by the outside textile printing company to print the pigment samples. Figure 3.3 is an image of the textile printer at Iowa State University, used for printing the reactive samples.

Figure 3.3 Mimaki TX2 1600 Textile Printer

Post-Treatment. After printing, all paper backing of the reactive fabric samples was removed. All reactive fabric samples were steamed for 60 minutes in an industrial steamer to set the dyes and inks into the fibers. Samples were steamed all at once at the same time.

Testing

Colorfastness to Laundering: Accelerated. Both the reactive and pigment samples were tested for washing in accordance to the AATCC standard Colorfastness to Laundering: Accelerated, test method 61-2013 (AATCC, 2015). Five samples each of reactive cotton sateen, reactive cotton duck, reactive cotton canvas, reactive cotton twill, reactive cotton percale, pigment cotton sateen, pigment cotton twill, pigment cotton lawn, pigment Basic Cotton Ultra, and pigment Kona® Cotton were cut into 2"x6" strips. An SDl Atlas Launder-Ometer machine was used to conduct the laundering test as seen in Figure 3.4. A 2"x"2 multi-fiber test fabric swatch was inserted in the canister with each printed sample as seen in Figure 3.5.

Figure 3.4 SDL Atlas Launder-Ometer

Figure 3.5 Multifiber Test Fabric

The Launder-Ometer machine and canisters were pre-heated to 45ºC and held at this temperature throughout testing. Five different Launder-Ometer tests were conducted. For test 1A, one steel lever lock canister was filled with 200 mL of distilled water, 10 steel balls, and .74g of detergent. For test 2A, one steel lever lock canister was filled with 150 mL of distilled water, 50 steel balls, and .225g of detergent. For test 3A, one steel lever lock canister was filled with 50 mL of distilled water, 100 steel balls, and .075g of detergent. For test 4A, one steel lever lock canister was filled with 50 mL of distilled water, 100 steel balls, .075g of detergent, and .0075g of bleach. For test 5A, one steel lever lock canister was filled with 150 mL of distilled water, 50 steel balls, .225g of detergent, and .0405g of bleach. The machine ran for 45 minutes after being fully loaded. After laundering, the samples were removed and rinsed three separate times in distilled waters. The samples were laid flat to dry.

Colorfastness to Light. The pigment and reactive samples were tested to see the affect light has on digitally printed textiles. AATCC test method 16.3-2015 Colorfastness to Light: Xenon- Arc was used to conduct this test (AATCC, 2015). The AATCC blue wool lightfastness standard was tested to determine the amount of time samples should be tested; in this case it was eight hours. Option three, Xenon-Arc Lamp, Continuous Light, Black Panel. A Suntest XLS+ machine was used to conduct the test as seen in Figure 3.6.

Figure 3.6 Suntest XLS+ Machine

The machine was set to Xenon continuous light on with the black panel temperature set to 63±1°C , the chamber air temperature to 43±2°C, and the humidity at 30% (AATCC, 2015). The pigment and reactive test samples were set in the Suntest XLS+ machine for exactly 8 hours.

Colorfastness to Perspiration. The digitally printed pigment and reactive samples were tested using AATCC test method 15-2013, Colorfastness to Perspiration, to determine the fastness of digitally printed inks to the effects of perspiration (AATCC, 2015). The acid perspiration solution was created from 1L distilled water, 10 ± 0.01 g sodium chloride (NaCl), 1 ± 0.01 g lactic acid, 1 ± 0.01 g sodium phosphate, dibasic anhydrous (Na_2HPO_4), and 0.25 ± 0.001 g l-histidine monohydro-chloride ($C_6H_9N_3O_2 \cdot HCl \cdot H_2O$) (AATCC, 2015). The perspiration solution was tested for the pH balance, ensuring it fell between the 4.3 ± .02 standard. The samples were then soaked in the solution for 30 minutes and ensured they weighed 2.25± 0.05 times the fabric samples original weight. Each test sample was placed on top of a multi-fiber test fabric stripes running perpendicular to the long dimension of the Petri dish. The Petri dishes were placed in a horizontal perspiration tester along with the top dual plates as seen in Figure 3.7.

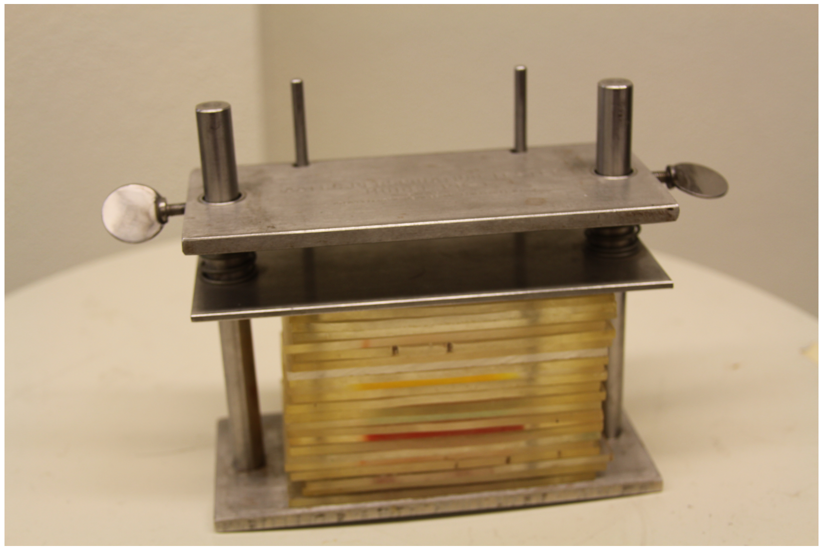


Figure 3.7 AATCC Perspiration Tester

A 3.63kg weight was placed on top of the dual plates to add extra pressure; the dual plates were then locked into place. The horizontal perspiration tester was placed in a vacuum oven with a constant temperature of 38±1°C for approximately 6 hours as seen in Figure 3.8.

Figure 3.8 Vacuum Oven

Color Fastness to Crocking. The purpose of the crocking test on digitally printed fabrics is to determine the amount of color transferred to other surfaces by rubbing. This test will follow the AATCC Test Method 8-2013 Colorfastness to Crocking: Crockmeter Method (AATCC, 2015). A dry and wet crockmeter test was conducted using an AATCC official crockmeter as seen in figure 3.9.

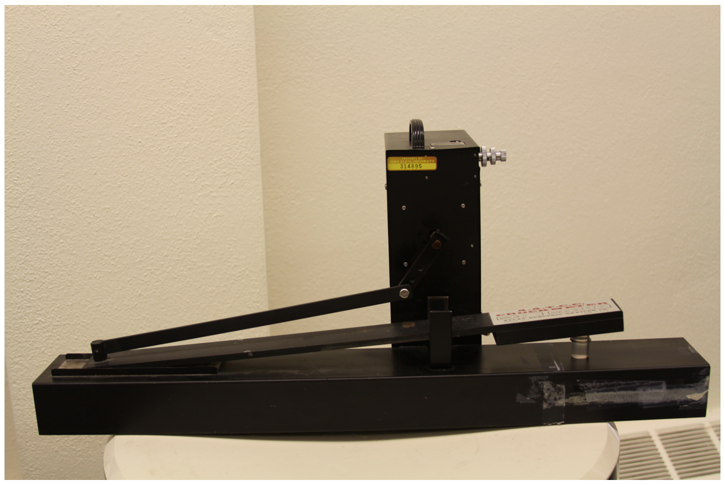


Figure 3.9 AATCC Crockmeter

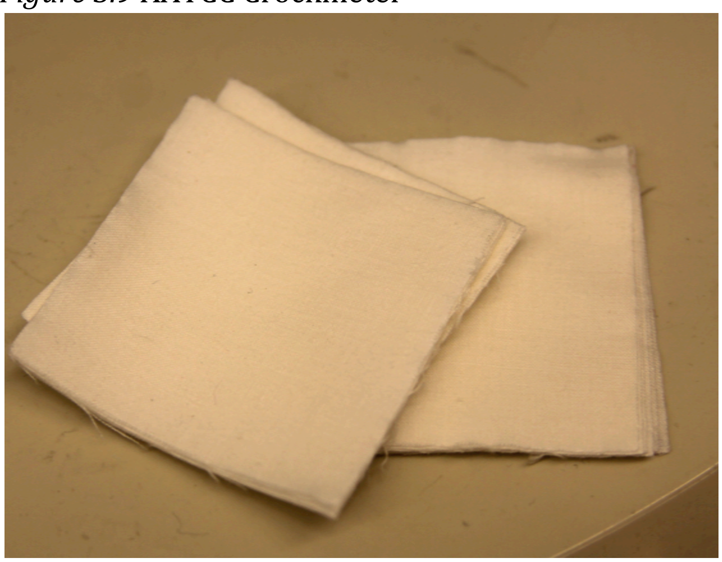


Figure 3.10 2x2" Crocking Test Cloths

For the dry test a test sample was laid on the base of the crockmeter parallel to the direction of rubbing, crocking test cloth square (Figure 3.10) was placed on the finger of the crockmeter securing it with a spiral wire. The motorized tester was set for the crockmeter to complete 10 full turns of rubbing. The finger was lowered onto the test sample and while rubbing color transferred from the sample to the test cloth square.

For wet crocking, distilled water was used to wet the crocking test cloth squares .65 times the original weight of the crock square. The test cloth weighed in at .26g therefore the amount of water added to each square was .17mL to achieve a 65±5% pickup. The test cloth square was then placed on the finger of the crockmeter and the test ran just as it did in the dry crocking test.

Color Measurement

The spectrophotometer, Cary 300 UV-Vis, was used to read the color intensity after each test as seen in Figure 3.11.

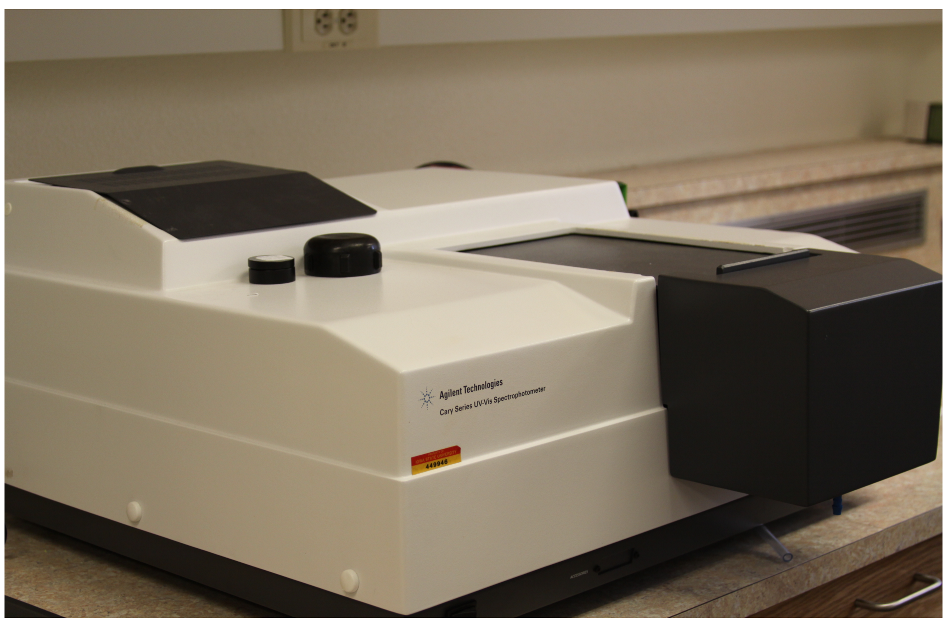


Figure 3.11. Cary UV-Vis 300 Spectrophotometer

The CIELAB coordinates were obtained from the spectrophotometer test. All of the results were compared to distinguish which ink set produces the best results. Results were compared to see if different tests have different effects on different types of inks.

The instrument that measures the ratio of the reflectance from a sample at numerous points across the visible spectra is called a spectrophotometer (Bae 2007, McDonald 1997). Spectrophotometers measure~~s~~ light beam's intensity by the color using photometers. Each color swatch printed on the multiple fabrics was tested with an instrument such as the spectrophotometer. The colors were tested before steaming, after steaming, after completing the home wash cycle, after going through the Launder-Ometer, light-fastness test, crocking test, and perspiration test.

Besides using the spectrophotometer, some tests require the use of the AATCC Gray Scale for Color Change and 9-Step Chromatic Transference Scale as seen in Figures 3.12 and 3.13.

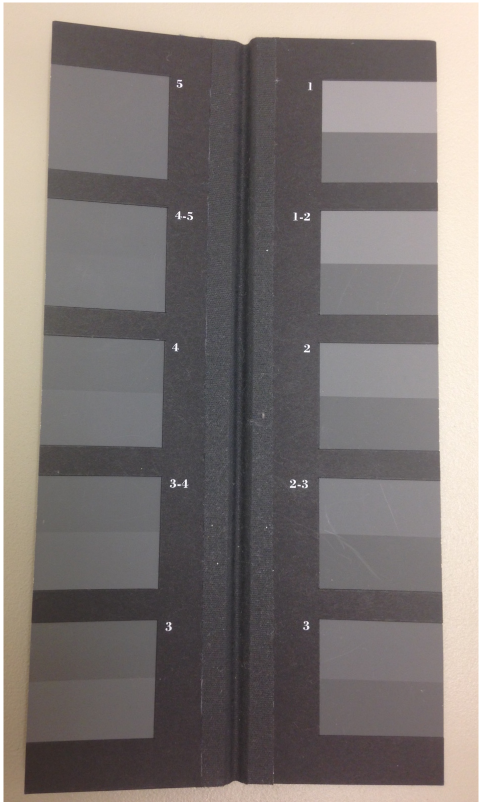


Figure 3.12 AATCC Gray Scale

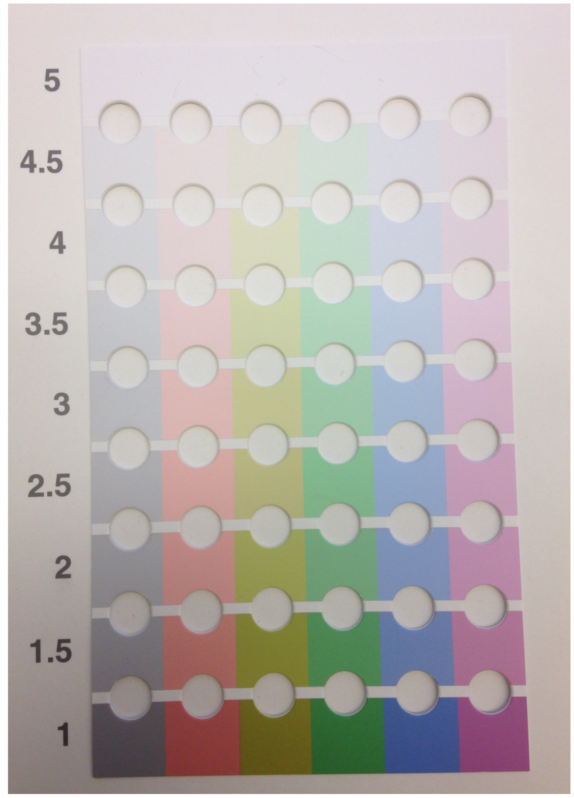


Figure 3.13. 9-Step Chromatic Transference Scale

The gray scale for color change is the AATCC evaluation procedure 1-2012 (AATCC, 2015). The gray scale is used by placing an original piece of an untested sample next to the tested sample side by side and then placing them next to the gray scale placing the gray mask over the samples. The samples and gray scale are looked at under a color checker machine under the “daylight” settings. The perceived visual difference between the original sample and the tested sample were compared to the perceived difference of the gray scale samples. The colorfastness number chosen was the gray scale sample that most accurately corresponded with the color difference of the sample. A grade of 5 is given when there is no color change and 1 is given for the most color change (AATCC, 2015).

The 9-Step Chromatic Transference Scale is AATCC evaluation procedure 8-2010 (AATCC, 2015). The purpose of the evaluation procedure is to visually compare the color of stained cloth and unstained cloth to the difference in color on the scale. The scale uses 54 color chips of red, yellow, green, blue, and purple. Using a color checker under the “daylight” settings the stained fabric was placed behind the transference scale and matched to the appropriate shade of color. A grade of 5 was given for fabric with no visible color transfer and 1 was given for the most color transfer (AATCC, 2015).

The ΔE* color change was obtained for each sample, as well. The ΔE* color change is the difference in color of the original sample and the tested sample. The higher the ΔE* number equals the more extreme color loss. The closer to 0 the number is equals a smaller amount of color lost.

To calculate the significance of color loss the ΔE* color change and the CIELAB color was tested using the Wilcoxon rank sum test to find the significance of colorfastness between the reactive and pigment inks.

CHAPTER 4. RESULTS

Overview

Fifty cotton textile samples were printed with a design consisting of red, blue, and green hues, with reactive and pigment inks. Cotton sateen and cotton twill were printed with both reactive and pigment inks, while the following six cotton fabrics were printed with only pigment inks, since the commercial printer had these fabrics: (a) lawn, (b) Kona ultra cotton plain weave, (c) basic cotton plain weave, (d) cotton percale (e) cotton duck and (f) cotton canvas. Using the AATCC standards all the samples were tested for fastness by laundering, light, crocking, and perspiration standards. The results for this experiment are reported in two sections to answer the initial research questions:

1. What are the colorfastness differences for fiber reactive inks versus pigment inks printed on cotton sateen and cotton twill in regards to AATCC test standards for: (a) laundering, (b) crocking, (c) light, and (d) perspiration?

2. What are the initial color value differences between specific cotton fiber fabrics printed with fiber reactive inks versus pigment inks, when tested under AATCC test standards for: (a) laundering, (b) crocking, (c) light, and (d) perspiration?

Colorfastness Differences between Cotton Twill and Sateen

AATCC standards for laundering, crocking, lightfastness, and perspiration were used to compare the colorfastness differences for reactive inks and pigment inks printed on cotton twill and cotton sateen. Each set of reactive printed samples were compared to the pigment set of samples reading the ΔE value with a Cary Series UV-Vis Spectrophotometer and by conducting the AATCC Gray Scale for Evaluating Change in Color, while color staining was evaluated by using the AATCC

9 Step Chromatic Transference Scale. The goal of these experiments was to understand the feasibility of reactive and pigments inks on natural fibers in a variety of conditions in which they may be used.

Laundering

Ten, 2"x6," cotton twill (n=5) and cotton sateen (n=5) samples, digitally printed with reactive inks and pigment inks, were tested using the AATCC standard Colorfastness to Laundering: Accelerated, test method 61-2013. Each fabric type was tested five times, tests A1-A5, in a steel lever lock canister along with a multi-fiber test cloth in a AATCC approved Launder-Ometer, according to the AATCC test standards as outlined in Table 4.1.

Table 4.1. *AATCC Standard Tests for Laundering: Accelerated on Cotton Twill and Cotton Sateen Printed With Reactive Inks and Pigment Inks.*

Sample #	Amount of Distilled Water	# of Steel Balls	Amount of AATCC Detergent	Bleach
A1	200 mL	10	.74g	None
A2	150 mL	50	.225g	None
A3	50 mL	100	.075g	None
A4	50 mL	100	.075g	.0075g of bleach
A5	150 mL	50	.225g	.0405g of bleach

The results of the laundering test are reported in Table 4.2 in terms of the ΔE* color change. ΔE* color change is the difference in color of the original constant sample compared to the sample after testing. A relatively low number indicates little to no change in color between the original printed samples and laundered samples, while a higher number indicates a larger color loss. The Wilcoxon rank sum test was used to test the significance of color loss between the reactive and pigment twill samples, as well as the reactive and pigment sateen samples.

Table 4.2. *ΔE* Color Change of Digitally Printed Reactive and Pigment Twill and Sateen Samples for Colorfastness to Laundering: Accelerated*

Test	Hue	Reactive Twill ΔE*	Pigment Twill ΔE*	Reactive Sateen ΔE*	Pigment Sateen ΔE*
A1	Green	14.03*	1.17	5.39*	1.62
	Blue	11.80	1.28	6.35	1.29
	Red	9.09	1.17	5.82	0.34
A2	Green	17.31*	4.56	6.1*	4.61
	Blue	17.72	3.02	6.85	4.12
	Red	10.03	3.24	4.12	5.42
A3	Green	19.00*	5.28	4.76	14.28*
	Blue	17.79	4.49	6.16	8.07
	Red	18.02	6.18	2.85	9.81
A4	Green	18.48*	7.87	5.11*	4.57
	Blue	11.92	5.40	3.41	2.81
	Red	12.49	5.99	5.82	3.74
A5	Green	14.02*	2.08	5.14*	1.90
	Blue	13.46	2.03	5.65	1.13
	Red	10.80	2.09	1.79	1.82

* = statistically significant

Cotton Twill ΔE* Results. The values obtained from the ΔE* color changing test demonstrated significant color loss in the reactive twill samples as compared to pigment twill samples. Since reactive inks are absorbed into the fibers, while pigment inks sit on top of the surface, the loss of color in the reactive samples could be a result of the density of the cotton fibers and twill weave structure having a harder time completely absorbing the reactive inks into the fibers. *The significance level of the color loss of reactive verses pigment were all above 0.05 using the Wilcoxon Rank Sum test, meaning the color difference between the samples was statistically significant.* Figure 4.3 provides images of the best and worst laundering samples for pigment cotton twill and Figure 4.4 show the best and worst laundering results for reactive twill.

Figure 4.1 Best, worst, & original pigment twill samples

Figure 4.2 Best, worst, & original reactive twill samples

Cotton Sateen ΔE* Results. The reactive cotton sateen did not experience as much color loss as the reactive twill in laundering. The reactive sateen and the pigment sateen experienced similar color loss in different experiments. *The significance level of the color loss of reactive verses pigment in samples A1, A2, A4, and A5 were all above 0.05 using the Wilcoxon Rank Sum test, meaning the color difference between the samples was statistically significant.* However, experiment A3 was an outlier, since the pigment sateen in this case lost significantly more color than the reactive sateen. *The significance level of the color loss of pigment verses reactive for A3 was above 0.05 using the Wilcoxon Rank Sum test, meaning the color difference between the samples was statistically significant.* Experiment A3 was tested four times more to ensure its validity. Experiment A3 has the least amount of water with the largest amount of steel balls creating the most agitation; therefore, these conditions may have hindered the colorfastness of pigment dyes on the cotton sateen fabrics. Figure 4.3 provides images of the best and worst laundering samples for pigment cotton sateen and Figure 4.4 show the best and worst laundering results for reactive sateen.

Figure 4.3 Best, worst, & original pigment sateen samples

Figure 4.4 Best, worst, & original reactive sateen samples

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. Table 4.3 contains the fastness to washing gray scale ratings and 9-step chromatic transference scale for staining for the digitally printed reactive and pigment ink twill samples. For the change in color using the gray scale, a grade of *5 is the best*, meaning no color loss, while a grade of *1 is the lowest*. A Colorfastness rating lower than grade 3 indicates a considerable visible alteration in color after washing. For color transfer or staining, the multi-fiber test swatches were compared to the 9-step chromatic transference scale. A rating of *5 indicated no staining* on the test swatch while a *1 indicated the most staining*. Figure 4.3 provides images of the best and worst laundering samples for pigment cotton twill and Figure 4.4 show the best and worst laundering results for reactive twill.

Table 4.3. *Gray Scale Color Change Ratings for Colorfastness to Washing of Digitally Printed Reactive and Pigment Inks on Cotton Twill and Sateen Samples*

Wash	**Cotton Fabrication**	**Change In Color (Gray Scale Grade)**			**Staining (9 Step*)**
		Green	Blue	Red	
A1	Pigment Twill	5	5	5	4.5
A1	Reactive Twill	2-3	3	3	4
A1	Pigment Sateen	5	4-5	5	5
A1	Reactive Sateen	4-5	4-5	4	4.5
A2	Pigment Twill	5	4-5	5	5
A2	Reactive Twill	1	1	1	4.5
A2	Pigment Sateen	4-5	4	4-5	4.5
A2	Reactive Sateen	4-5	4-5	4	4.5
A3	Pigment Twill	5	4-5	5	5
A3	Reactive Twill	1	1	1	2
A3	Pigment Sateen	4-5	4	3-4	3.5
A3	Reactive Sateen	4-5	4	4-5	2.5
A4	Pigment Twill	5	4	4-5	4.5
A4	Reactive Twill	1-2	1-2	1-2	2.5
A4	Pigment Sateen	5	4	4-5	4.5
A4	Reactive Sateen	5	4-5	4	2
A5	Pigment Twill	5	4-5	5	4.5
A5	Reactive Twill	1-2	1-2	1-2	4
A5	Pigment Sateen	5	4-5	4-5	4.5
A5	Reactive Sateen	4-5	4	4	4.5

*9 Step Chromatic Transference Scale

The reactive samples experienced much more color loss compared to the pigment in both the twill and the sateen. *Twelve of the 15 reactive twill color samples had ratings between 1-2, experiencing the most color loss* according to the 9-step chromatic transference scale. In contrast, *Test A1 produced the best outcome for both* *fabrics* having no visual difference in color for the pigment ink samples and only a slightly visible color difference for the reactive samples. The ratings obtained for staining of the pigment samples were excellent, with all except 1 test swatch scoring 4.5 or above. *The one outlier, A3, pigment sateen, scored a 3.5 on the staining scale and had the worst change in color as well.*

CIELAB Colorfastness Results. The color readings from the CIELAB colors from the spectrophotometer, in Table 4.4, support the findings obtained by the ΔE* color change, gray scale, and 9-step chromatic transference scale.

Table 4.4. *Colorfastness to Washing of Digitally Printed Reactive Ink and Pigment Ink Cotton Twill and Sateen Samples CIELAB Color*

Wash	Cotton Fabric	Hue	CIELAB Color Reading		
			L*	a*	b*
A1	Pigment Twill	Green	55.7855	-29.2470	39.0981
		Blue	24.1288	2.7293	-31.8616
		Red	44.9947	51.7993	43.4228
A1	Reactive Twill	Green* (.593)	55.4231	-27.1867	23.4933
		Blue* (.109)	30.1508	8.6578	-22.5035
		Red* (.109)	42.7917	43.3316	21.5664
A1	Pigment Sateen	Green	58.7591	-27.3679	44.2867
		Blue	26.7665	-1.6476	-34.0612
		Red	46.8138	52.3385	47.7521
A1	Reactive Sateen	Green* (.109)	43.6793	-40.2919	15.3071
		Blue* (1.000)	23.1497	-3.9048	-30.2804
		Red* (.109)	42.4956	42.6468	32.6534
A2	Pigment Twill	Green	54.8323	-27.6512	36.3384
		Blue	24.782	-3.2798	-30.0472
		Red	45.7685	44.9814	31.9910
A2	Reactive	Green* (1.000)	56.9121	-23.0928	22.2805

Table 4.4 (continued)

	Twill				
		Blue* (.109)	33.5074	6.7458	-20.1723
		Red* (.109)	45.2080	37.2573	17.4262
A2	Pigment Sateen	Green	58.2690	-26.7524	42.6783
		Blue	29.8087	-1.3315	-30.4442
		Red	47.2503	50.9600	44.8995
A2	Reactive Sateen	Green* (.109)	44.5663	-39.0276	17.3977
		Blue* (1.000)	23.4879	-4.3994	30.1427
		Red* (.109)	43.7342	42.8338	33.1675
A3	Pigment Twill	Green	52.6889	-27.2380	34.7971
		Blue	23.8863	-3.8402	-29.9350
		Red	43.2247	48.4020	38.9951
A3	Reactive Twill	Green* (.593)	49.7036	-21.8314	13.5159
		Blue* (.109)	32.6687	4.2123	-20.4280
		Red* (.109)	41.4531	30.8812	11.9901
A3	Pigment Sateen	Green	58.8247	-22.3210	36.5199
		Blue	30.5730	-1.0091	-28.8055
		Red	46.6331	47.7584	41.2565
A3	Reactive Sateen	Green* (.109)	43.3291	-38.9450	15.4179
		Blue* (.109)	23.1682	-3.9187	-29.0481
		Red* (.109)	40.7107	37.7937	27.8044
A4	Pigment Twill	Green	52.7305	-27.0371	36.1760
		Blue	24.2895	-4.0080	-29.1899
		Red	42.1891	45.0966	35.3283
A4	Reactive Twill	Green* (.593)	52.3187	-21.8792	15.0290
		Blue* (.109)	31.9679	5.7909	-20.8644
		Red* (.109)	42.1929	38.7426	18.0742
A4	Pigment Sateen	Green	58.6396	-26.4575	42.2252
		Blue	27.6544	-1.5270	-32.4510
		Red	46.9015	50.4835	44.6198
A4	Reactive Sateen	Green* (.109)	42.4661	-38.5946	15.2753
		Blue* (.285)	22.6869	-3.9788	-30.6343
		Red* (.109)	42.1808	43.1396	32.9557

Table 4.4 (continued)

A5	Pigment Twill	Green	55.1638	-28.7916	38.0141
		Blue	24.3943	-2.8654	-31.4699
		Red	44.9727	50.5394	41.3226
A5	Reactive Twill	Green* (1.000)	55.5552	-25.8970	22.1454
		Blue* (.109)	31.9151	7.4170	-22.2945
		Red * (.109)	43.8431	40.2114	19.3650
A5	Pigment Sateen	Green	59.1261	-27.8538	44.5469
		Blue	27.1086	-1.3794	-33.0846
		Red	47.1766	51.6183	46.1551
A5	Reactive Sateen	Green* (.109)	43.9313	-41.1741	14.5459
		Blue* (.285)	22.5978	-4.0397	-30.8504
		Red* (.109)	43.3689	45.0098	34.6111

* indicates statistical significance

All of the CIELAB colors for pigment and reactive samples readings were analyzed statistically with the Wilcoxon Rank Sum Test in the Statistical Package for the Social Sciences software to determine any significance between color differences. The CIELAB colors for pigment inks had a higher intensity than the reactive inks. *The significance level of the color difference of pigment verses reactive for all samples was above 0.05 using the Wilcoxon Rank Sum test, demonstrating that color strength is better with pigment inks.*

Even though for test A3 the pigment sateen sample was significant for the ΔE* color change test it was not significant when testing the CIELAB color. This can occur because the color strength of the pigment sateen was initially better than the reactive sateen. *Both samples experienced color loss and even with the one-outlier sateen sample, reactive inks still lost enough color to create a statistical significance.*

Crocking

Six, 2"x6," cotton twill (n=3) and cotton sateen (n=3) samples, digitally printed with reactive inks and pigment inks, were tested using the crockmeter method in accordance to the AATCC test method 8-2013. In this test the red, blue, and green were all tested separately to conclude which colors performed the best for crocking. An A.A.T.C.C. crockmeter was used to complete 10 full turns of the crocking finger and the test cloth, rubbing the testing sample at the rate of one turn per second. A dry crocking and wet crocking test was conducted. For the wet crocking test .17mL of water was added to each crocking test cloth. The Wilcoxon rank sum test was used to test the significance of color loss between the reactive and pigment twill samples as well as the reactive and pigment sateen samples from both dry and wet crocking.

Cotton Twill and Cotton Sateen ΔE Results. The results of the colorfastness to crocking are reported in Table 4.5 in terms of the ΔE* color change. ΔE* color change is the difference in color of the original constant sample compared to the sample after testing.

Table 4.5 *ΔE* Color Change of Digitally Printed Reactive and Pigment Twill Samples for Dry & Wet Crocking Test*

Test	Hue	Reactive Twill ΔE*	Pigment Twill ΔE*	Reactive Sateen ΔE*	Pigment Sateen ΔE*
Dry Crocking	Green	3.57*	1.75	.80*	.82
	Blue	1.39	1.43	.91	1.21
	Red	.89	1.64	.87	.52
Wet Crocking	Green	3.61*	1.50	.4*	1.19
	Blue	1.21	1.73	1.47	1.77
	Red	2.29	1.46	1.42	1.62

Pigment twill and pigment sateen lost the least amount of color during crocking. Pigment and reactive twill lost more color than pigment and reactive sateen during both crocking tests. The larger color loss could be due to the cotton twill not absorbing as much of the ink, allowing more ink to be transferred to the test cloth during rubbing. There was not a drastic difference in colors between the dry and wet crocking tests. All colors of both reactive and pigment samples were within 2.00 of each other between both tests. *The significance level of the color loss of reactive verses pigment were all above 0.05 using the Wilcoxon Rank Sum test, meaning the color difference between the samples was statistically significant for both wet and dry crocking.*

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. Table 4.6 contains the fastness to crocking gray scale ratings for the digitally printed reactive and pigment ink twill samples. For the change in color using the gray scale, a grade of *5 is the best*, meaning no color loss, while a grade of *1 is the lowest*. A Colorfastness rating lower than grade 3 indicates a considerable visible alteration in color after washing. For color transfer or staining, the multi-fiber test swatches were compared to the 9-step chromatic transference scale. A rating of *5 indicated no staining* on the test swatch while a *1 indicated the most staining*.

Table 4.6 *Change in Color and Staining of Digitally Printed Reactive and Pigment Twill Samples for Dry & Wet Crocking Test*

Cotton Fabrication	**Hue**	**Dry Crocking Change In Color (Gray Scale Grade)**	**Dry Crocking Staining (9 Step*)**	**Wet Crocking Change In Color (Gray Scale Grade)**	**Wet Crocking Staining (9 Step*)**
Pigment Twill	Green	4	1.5	4-5	1.5
	Blue	3-4	1	3	1
	Red	4-5	1	4	1
Reactive Twill	Green	3	2.5	4	2.5
	Blue	3-4	3	4	1.5
	Red	3-4	3	4	2.5
Pigment Sateen	Green	4-5	2.5	4-5	2
	Blue	4	1.5	4-5	1.5
	Red	4-5	1.5	4	2
Reactive Sateen	Green	4	4	4-5	2
	Blue	4	4	4-5	1.5
	Red	4	4.5	4	2

Visually, the pigment samples obtained very close to the same change in color ratings as the reactive samples. *All ratings were 3 or above meaning that there was not a visually drastic difference in the original sample and the tested sample*. Pigment *twill blue is the only pigment sample to receive a rating of ~~a~~ 3* and is the only pigment sample to perform worse than the reactive sample.

The test cloths of the pigment samples obtained a lower rating for staining than the reactive samples. *All of the pigment samples were a 2.5 or below with 1/3 of the samples receiving a rating of a 1 meaning the most staining possible according to the 9-step chromatic transference scale occurred*. Ratings were fairly consistent between the wet and dry crocking for the pigment samples. A possible reason why the pigment samples crocked worse than the reactive samples is because the pigment inks sit on top of the fabric, therefore allowing excess color to be transferred to the test cloth. Wet crocking had a larger impact on staining for the reactive samples than the dry crocking did. The reactive samples had moderate to low staining for dry crocking with one rating at 2.5 and the rest above a 3. *All of the wet crocking staining for the reactive samples was below a 2.5*. A possible reason for such a difference in staining between the wet and dry crocking is that if there were any excess inks in the reactive samples that did not get washed out during the laundering process, once the sample was wetted, it may have allowed the excess inks to be rubbed out.

CIELAB Colorfastness Results. The colorfastness results concluded from crocking test in regards to CIELAB color were consistent with the results of the ΔE* color change as reported in Table 4.7.

Table 4.7. *CIELAB Color Strength of Digitally Printed Pigment and Reactive Samples of Cotton Twill and Cotton Sateen*

Cotton Fabrication	Test	Hue	CIELAB Color Reading		
			L*	a*	b*
Pigment Twill	Dry Crocking	Green	54.7092	-28.1543	38.4321
		Blue	23.4963	-3.3767	-32.6994
		Red	45.0382	51.8836	43.8135
Reactive Twill		Green* (.109)	49.2461	-33.6807	20.9171
		Blue* (.285)	23.4963	-3.3767	-32.6994
		Red* (.109)	38.5273	46.5719	24.6822
Pigment Sateen	Dry Crocking	Green	59.3154	-28.3078	45.6509
		Blue	25.6928	-1.9331	-34.4184

Table 4.7(Continued)

		Red	47.3287	50.6104	44.0301
Reactive Sateen		Green* (.109)	40.7150	-41.5747	13.2369
		Blue* (.593)	19.6161	-3.1090	-29.2968
		Red* (.109)	41.0996	46.5419	32.0027
Pigment Twill	Wet Crocking	Green	54.6884	-28.2123	37.3343
		Blue	23.3790	-3.5564	-32.4184
		Red	45.1473	50.9199	41.9839
Reactive Twill		Green* (.109)	47.3402	-35.9670	17.4567
		Blue* (.285)	22.2105	5.1101	-25.4995
		Red* (.109)	38.6315	47.0811	25.0726
Pigment Sateen	Wet Crocking	Green	59.4346	-28.5369	45.8204
		Blue	25.6302	-1.7610	-35.0648
		Red	47.1278	52.2992	46.1417
Reactive Sateen		Green* (.109)	41.7143	-36.8312	15.8209
		Blue* (1.000)	20.9321	-2.8059	-28.1483
		Red* (.109)	40.4809	45.8760	32.6880

* indicates statistical significance

All of the CIELAB colors for pigment and reactive samples readings were analyzed statistically with the Wilcoxon Rank Sum Test in the Statistical Package for the Social Sciences software to determine if any significance between color differences.

The CIELAB colors for pigment inks had a higher intensity than the reactive inks. *The significant difference between both pigment and twill CIELAB colors was above 0.05 using the Wilcoxon Rank Sum test, demonstrating that color strength is better with pigment inks.*

Perspiration

Two, 2”x6,” cotton twill (n=1) and cotton sateen (n=1) samples, digitally printed with reactive inks and pigment inks, were tested in accordance to the AATCC test method 15-2013, colorfastness to perspiration, and the digitally printed samples were soaked for 30 minutes in an acid perspiration solution as shown in Table 4.8. Each sample was mounted to a multi-fiber test cloth sandwiched between Petri dishes. The samples were placed in a vacuum oven at 37°C for 6 hours.

Table 4.8 *Acid Perspiration Solution*

Distilled Water	Sodium Chloride	Lactic Acid	Sodium Phosphate, Dibasic, Anhydrous	Histodine Monohydro-chloride
1L	10g	1g	1g	.25g

Cotton Twill and Cotton Sateen ΔE Results. The results of the colorfastness to perspiration are reported in Table 4.9 in terms of the ΔE* color change. ΔE* color change is the difference in color of the original constant sample compared to the sample after testing.

Table 4.9. *ΔE* Color Change of Digitally Printed Reactive and Pigment Twill and Sateen Samples for Perspiration Test*

Test	Hue	Reactive Twill ΔE*	Pigment Twill ΔE*	Reactive Sateen ΔE*	Pigment Sateen ΔE*
Perspiration	Green	14.52*	3.33	6.83*	1.31
	Blue	14.51	4.23	8.61	1.62
	Red	14.98	4.86	8.34	1.19

* indicates statistical significance

The reactive twill and sateen samples had a statistically significant color loss compared to the pigment samples. The twill samples experienced more color loss than the sateen samples. The least amount of color loss happened for the color green in all the samples. Overall, the perspiration had a large impact on the overall color of all samples. *The significant difference between both pigment and twill colors was above 0.05 using the Wilcoxon Rank Sum test, demonstrating that color strength is better with pigment inks.*

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. Table 4.10 contains the fastness to perspiration gray scale ratings for the digitally printed reactive and pigment ink twill samples.

Table 4.10. *Change in color and staining of digitally printed reactive and pigment twill and sateen samples for perspiration test*

Cotton Fabrication	Hue	Change In Color (Gray Scale Grade)	Staining (9 Step*)
Pigment Twill	Green	5	5
	Blue	5	4.5
	Red	5	5
Reactive Twill	Green	2-3	3.5
	Blue	2-3	3.5
	Red	1-2	3.5
Pigment Sateen	Green	5	5
	Blue	5	5
	Red	5	5
Reactive Sateen	Green	4	5
	Blue	4	5
	Red	4	4.5

The pigment samples showed no visual difference in color change with all samples receiving the rating of a 5. All pigment samples but one received a staining rating of a 5, meaning no staining was visible on the test cloth. The pigment blue sample received a 4.5 rating for staining, showing very minimal staining on the test cloth. The reactive samples did not perform as well as the pigment samples in the perspiration test. The reactive twill experienced more color loss and staining than the reactive sateen. *The significant difference between both pigment and twill colors was above 0.05 using the Wilcoxon Rank Sum test, demonstrating that color strength is better with pigment inks.*

CIELAB Colorfastness Results. The colorfastness results concluded from the perspiration test in regards to CIELAB color were consistent with the results of the ΔE* color change as reported in Table 4.11.

Table 4.11. *CIELAB Color Strength of Digitally Printed Reactive and Pigment Twill and Sateen Samples for Perspiration Test*

Cotton Fabrication	Hue	CIELAB Color Reading		
		L*	a*	b*
Pigment Twill	Green	55.1186	-29.2678	39.4274
	Blue	23.5062	-3.1197	-32.2317
	Red	44.3197	51.1615	43.6666
Reactive Twill	Green* (.109)	48.6746	-34.9749	17.4066
	Blue* (.109)	26.3500	3.7052	-26.0285
	Red* (.109)	41.1604	44.9446	22.9430
Pigment Sateen	Green	58.5464	-27.1180	44.4691
	Blue	26.0040	-1.8058	-34.2423
	Red	46.7516	52.4683	47.6888
Reactive Sateen	Green* (.109)	42.6202	-39.1418	16.9433
	Blue* (1.000)	22.7079	-2.9982	-28.1123
	Red* (.109)	42.1178	45.2929	33.1649

* indicates statistical significance

The color difference between the pigment and sateen samples was all statistically significant. The colors of the pigment samples were much more intensified compared to the reactive samples. The largest differences occurred in the color green of both the twill and sateen samples. *The significant difference between both pigment and twill colors was above 0.05 using the Wilcoxon Rank Sum test, demonstrating that color strength is better with pigment inks.*

Lightfastness

Colorfastness to light was tested using two, 2"x6," cotton twill (n=1) and cotton sateen (n=1) samples, digitally printed with reactive inks and pigment inks, using the AATCC test method 16.3-2012, colorfastness to light: Xenon-Arc, option 3, Xenon-Arc lamp, continuous light, black panel option. The pigment and reactive samples were tested using a Suntest XLS+ for 8 hours with the black panel temperature set to 63°C, chamber are temperature to 43°C, and the humidity at 30%.

Cotton Twill and Cotton Sateen ΔE Results. The results of the colorfastness to light are reported in Table 4.12 in terms of the ΔE* color change. ΔE* color change is the difference in color of the original constant sample compared to the sample after testing.

Table 4.12. *ΔE* Color Change of Digitally Printed Reactive and Pigment Twill Samples for Lightfastness Test*

Hue	Reactive Twill ΔE*	Pigment Twill ΔE*	Reactive Sateen ΔE*	Pigment Sateen ΔE*
Green	3.57*	1.73	.65*	1.11
Blue	3.25	3.50	1.04	.85
Red	.84	1.81	3.68	1.21

* indicates statistical significance

The effects of light on the digital printed samples were not consistent. Reactive twill green had a larger color loss than the pigment twill green. Pigment twill blue and red had a larger color loss than reactive blue and red. Pigment sateen green had a larger color loss than reactive green and reactive sateen blue and red had a larger color loss than pigment sateen. *The significant difference between both pigment and twill colors was above 0.05 using the Wilcoxon Rank Sum test, demonstrating that color strength is better with pigment inks.*

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. Table 4.13 contains the fastness to light gray scale ratings for the digitally printed reactive and pigment ink twill and sateen samples.

Table 4.13. *Change in Color of Digitally Printed Reactive and Pigment Twill Samples for Lightfastness Test*

Cotton Fabric	Colors	Change In Color (Gray Scale Grade)
Pigment Twill	Green	5
	Blue	5
	Red	5
Reactive Twill	Green	4
	Blue	4
	Red	4-5
Pigment Sateen	Green	5
	Blue	5
	Red	5
Reactive Sateen	Green	5
	Blue	4-5
	Red	4-5

All pigment samples received a rating of a 5, meaning that there was no visual difference in color. Reactive twill and sateen all received ratings of 4 or higher with reactive sateen performing slightly better than the twill. *The significant difference* *between both pigment and twill colors was above 0.05 using the Wilcoxon Rank Sum test, demonstrating that color strength is better with pigment inks.*

CIELAB Colorfastness Results. The colorfastness results concluded from the light test in regards to CIELAB color were consistent with the results of the ΔE* color change as reported in Table 4.14.

Table 4.14. *Change in Color of Digitally Printed Reactive and Pigment Twill Samples for Lightfastness Test*

Cotton Fabrication	Hue	CIELAB Color Readings		
		L*	a*	b*
Reactive Twill	Green* (.109)	48.7758	-33.1139	20.5763
	Blue* (.109)	27.9940	2.4091	23.9999
	Red* (.109)	37.5081	45.1086	24.6300
Pigment Twill	Green	55.5242	-28.6156	38.7692
	Blue	23.9969	-3.3396	-31.5239
	Red	45.1375	51.8991	43.9525
Reactive Sateen	Green* (.109)	40.5064	-38.5356	14.2307
	Blue* (.593)	19.5708	-3.0748	-28.0838
	Red* (.109)	39.9857	44.6352	31.8648
Pigment Sateen	Green	59.0450	-28.6931	45.8491
	Blue	25.8643	-1.8516	-34.2277
	Red	47.0887	53.4324	49.1354

* indicates statistical significance

All reactive samples in Table 4.14 had a statistically significant color loss compared to the pigment samples. The largest color difference occurred between the reactive and pigment sateen samples. Reactive sateen had more color loss than reactive twill and pigment twill had more color loss than pigment sateen. *The significant difference between both pigment and twill colors was above 0.05 using the Wilcoxon Rank Sum test, demonstrating that color strength is better with pigment inks.*

The ΔE* color change for both reactive and pigment sateen and twill varied from test to test. To visually see the difference between each test the data was made into a bar graph. Refer to Figure A1 pigment twill, A2 pigment sateen, A6 reactive twill, and A7 reactive sateen.

Colorfastness Difference between Pigment Ink Digitally Printed Samples. All other pigment samples, printed on Basic Cotton Ultra, Kona® Cotton, and Cotton Lawn Ultra, from an outside professional printing company, were tested for colorfastness to laundering, crocking, perspiration, and light. All of the pigment samples were compared to each other reading the ΔE* value with a Cary Series UV-Vis Spectrophotometer and by conducting the AATCC Gray Scale for Evaluating Change in Color, while color staining was evaluated by using the AATCC 9 Step Chromatic Transference Scale. The goal of these experiments was to understand the colorfastness of pigments inks on natural fibers in a variety of conditions in which they may be used.

Laundering

Fifteen, 2”x6,” Kona® Cotton (n=5), Cotton Lawn Ultra (n=5), and basic cotton (n=5) samples, digitally printed with pigment inks, were tested using the AATCC standard Colorfastness to Laundering: Accelerated, test method 61-2013 as seen in table 4.15. Refer to table 4.1 A1-A5 laundering set-up.

Table 4.15. *ΔE* Color Change of Digitally Printed Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton.*

Test	Hue	Basic Cotton Ultra ΔE*	Kona® Cotton ΔE*	Cotton Lawn

Table 4.15 (continued)

				Ultra ΔE*
A1	Green	2.40	2.80	2.71
	Blue	1.17	1.61	2.33
	Red	.79	1.12	2.38
A2	Green	2.85	6.16	7.39
	Blue	1.15	3.22	3.61
	Red	1.80	3.91	5.25
A3	Green	3.87	8.69	9.94
	Blue	1.80	4.82	6.37
	Red	4.11	9.55	6.19
A4	Green	3.39	3.92	3.96
	Blue	1.07	1.18	8.01
	Red	.98	3.45	4.13
A5	Green	3.44	4.87	6.31
	Blue	1.65	1.54	3.21
	Red	4.10	4.99	7.79

Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton ΔE* Results. The wash that produced the *worst color results for all 3-fabric types was A3*, the same wash producing low colorfastness to the pigment sateen and twill samples, as well. Test A3 resulted in the best outcome. This could be due to test A1 having the largest volume of water, least amount of steel balls, and largest amount of detergent, therefore causing the least amount of agitation. Overall, *cotton lawn had the worst colorfastness* with the highest ΔE* color change at 9.94. No one color produced better results. *Overall, the samples had decent wash durability with 62% of the samples obtaining a rating of 4 or below*. Figure 4.5 exemplifies the best and worst laundering outcome of basic cotton, Figure 4.6 shows Kona® Cotton samples, and Figure 4.7 is Cotton Lawn Ultra samples.

Figure 4.5 Best, worst, & original pigment basic cotton samples

Figure 4.6 Best, worst, & original pigment Kona® Cotton samples

Figure 4.7 Best, worst, & original pigment Cotton Lawn Ultra samples

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. Using the AATCC gray scale for color change and 9-step chromatic transference scale for staining ratings were obtained in Table 4.16. Little color change was visible for the color green more than any other color, with 8 of the 15 ratings being a 5. Results were consistent with test A3 receiving the lowest ratings. All change in color ratings were a 3-4 or above meaning that visually, not much difference could be seen by the eye between the original and tested samples. There was no visible staining on the multi-fiber test cloth for any fabrics in test A1. The only staining under the rating of 4.5 occurred in the test A3 for both Kona® cotton and Cotton Lawn Ultra; both obtained a rating of 2.5. The ratings for staining were excellence.

Table 4.16. *Gray Scale Color Change Ratings for Colorfastness to Washing of Digitally Printed Pigment Inks on Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton*

Cotton Fabrication	**Wash**	**Change In Color (Gray Scale Grade)**			**Staining (9 Step*)**
		Green	Blue	Red	
Basic Cotton Ultra	A1	5	4-5	5	5
Kona® Cotton	A1	5	4-5	4-5	5
Cotton Lawn	A1	4-5	4-5	4-5	5

Table 4.16 (continued)

Ultra					
Basic Cotton Ultra	A2	5	4-5	5	5
Kona® Cotton	A2	5	3-4	4-5	5
Cotton Lawn Ultra	A2	4-5	4	4	4.5
Basic Cotton Ultra	A3	5	4	4	4.5
Kona® Cotton	A3	4-5	4	4-5	2.5
Cotton Lawn Ultra	A3	4-5	3-4	4	2.5
Basic Cotton Ultra	A4	4-5	4-5	4-5	4.5
Kona® Cotton	A4	5	4-5	4-5	4.5
Cotton Lawn Ultra	A4	4-5	3-4	4-5	4.5
Basic Cotton Ultra	A5	5	4-5	4-5	5
Kona® Cotton	A5	5	4-5	4-5	4.5
Cotton Lawn Ultra	A5	4-5	4	4	4.5

CIELAB Colorfastness Results. Table 4.17 consists of the CIELAB colors for each sample after washing. The results were consistent amongst the three tables of results. Basic Cotton Ultra, consistently produced the highest ratings, lowest ΔE* color change, and strongest CIELAB colors. Kona® Cotton produced the worst results out of the samples. The largest difference in color can be seen in the green samples.

Table 4.17. *ΔE* Color Change of Digitally Printed Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton.*

Cotton Fabrication	**Wash**	**Hue**	**CIELAB Color Reading**		
			L*	a*	b*
Basic Cotton Ultra	A1	Green	60.8630	-25.8524	43.0822
		Blue	30.8517	-4.1315	-33.2223
		Red	48.7951	50.3910	45.5663
Kona® Cotton	A1	Green	56.0392	-29.2665	41.5148
		Blue	29.4704	-4.3915	-33.5678
		Red	46.7534	50.6815	45.4920
Cotton Lawn	A1	Green	58.7824	-24.8857	43.1731

Table 4.17 (continued)

Ultra					
		Blue	27.3042	-0.6150	-30.8317
		Red	47.5752	51.2503	45.8377
Basic Cotton Ultra	A2	Green	60.7528	-26.3668	42.6940
		Blue	31.4709	-3.9476	-32.6860
		Red	48.9101	50.7093	45.9543
Kona® Cotton	A2	Green	55.8191	-29.2426	41.5148
		Blue	34.3443	-3.2930	-29.1634
		Red	46.8597	49.9664	43.5520
Cotton Lawn Ultra	A2	Green	58.9668	-24.3720	41.5922
		Blue	29.8304	-0.2042	-28.9736
		Red	47.8491	50.0848	44.0787
Basic Cotton Ultra	A3	Green	60.1010	24.6496	41.1242
		Blue	31.6299	-3.5054	-30.8854
		Red	49.6144	49.1267	42.9326
Kona® Cotton	A3	Green	55.6490	-27.5453	39.3175
		Blue	32.1100	-3.5273	-29.1785
		Red	46.5587	46.3728	39.0070
Cotton Lawn Ultra	A3	Green	58.2915	-22.0970	39.3067
		Blue	31.1327	0.0870	-27.6619
		Red	41.0255	47.8326	47.4935
Basic Cotton Ultra	A4	Green	60.3648	-25.9288	42.4921
		Blue	31.2201	-3.9381	-32.9165
		Red	48.8638	51.2077	47.0717
Kona® Cotton	A4	Green	55.7523	-29.9307	42.6301
		Blue	30.7311	-3.9287	-32.2179
		Red	47.3407	50.0263	43.9836
Cotton Lawn Ultra	A4	Green	58.4565	-24.5202	42.1642
		Blue	30.8339	-0.3086	-28.5086
		Red	46.9559	50.1133	44.4948
Basic Cotton Ultra	A5	Green	60.7084	-26.0535	42.6958
		Blue	31.4878	-3.7982	-32.5149
		Red	48.9262	50.7573	45.9926
Kona® Cotton	A5	Green	56.1796	-29.8687	42.8360

		Blue	31.2444	-3.7048	-31.7971
		Red	47.3226	50.6202	44.1657
Cotton Lawn Ultra	A5	Green	58.5640	-24.0647	42.1642
		Blue	29.7195	-0.5035	-29.5952
		Red	48.4151	50.1264	43.4141

Crocking

Nine, 2"x6," Kona® Cotton (n=3), Cotton Lawn Ultra (n=3), and basic cotton (n=3) samples, digitally printed with pigment inks, were tested using the crockmeter method in accordance to the AATCC test method 8-2013.

Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton ΔE* Results. A dry crocking and wet crocking test was conducted on all pigment samples and the ΔE* is reported in Table 4.18.

Table 4.18. *ΔE* Color Change of Digitally Printed Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton.*

Test	Hue	Basic Cotton Ultra ΔE*	Kona® Cotton ΔE*	Cotton Lawn Ultra ΔE*
Dry Crocking	Green	1.68	.68	4.29
	Blue	1.09	2.01	.78
	Red	1.16	1.12	.62
Wet Crocking	Green	1.47	4.71	6.57
	Blue	.25	1.20	1.83
	Red	1.85	.73	5.26

Basic Cotton Ultra produced the overall best washing results and also had the lowest ΔE* color change for both wet and dry crocking. Between the dry and wet crocking there was not one test that consistently produced the best results. Cotton Lawn Ultra obtained the highest change in color for both dry and wet crocking. The color green had the highest ΔE* color change among all samples.

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. Each pigment sample ~~s~~ obtained a rating for change in color and staining from the gray scale and 9-step chromatic transference scale as seen in Table 4.19.

Table 4.19 *Change in Color and Staining Of Digitally Printed Pigment Samples for Dry & Wet Crocking Test*

Cotton Fabrication	**Hue**	**Dry Crocking Change In Color (Gray Scale Grade)**	**Dry Crocking Staining (9 Step*)**	**Wet Crocking Change In Color (Gray Scale Grade)**	**Wet Crocking Staining (9 Step*)**
Basic Cotton Ultra	Green	4-5	1.5	4-5	2.5
	Blue	4	1	3-4	1.5
	Red	4-5	1.5	3-4	1.5
Kona® Cotton	Green	4-5	2.5	4	3
	Blue	4-5	2	3	2
	Red	4-5	2	3-4	1.5
Cotton Lawn Ultra	Green	4-5	1.5	4	3
	Blue	3-4	1	3	1.5
	Red	4-5	1.5	3-4	1.5

All but two samples for dry crocking obtained a rating of 4-5. Visually, the difference could be seen more in the wet crocking samples than the dry crocking. 6 of the 9 samples obtained ratings between 3 and 3-4. Excessive staining occurred on the test cloth for the crocking tests. For the pigment samples the dry crocking stained more than the wet crocking. Basic Cotton Ultra and Cotton Lawn Ultra obtained the worst ratings, 1.5 or below, meaning the most possible staining occurred. The color blue stained more than any other color. Kona® Cotton experienced moderate staining with most ratings around a 2. Although the crocking doesn't directly have a large impact on the overall color of the sample, an excessive amount of staining or transfer will occur.

CIELAB Colorfastness Results. There was minimal difference in the CIELAB colors of the crocking samples seen in Table 4.20 compared to the original CIELAB samples. Basic cotton, again, produced the best color results.

Table 4.20 .*CIELAB Color Strength of Digitally Printed Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton*

Cotton Fabrication	**Test**		**CIELAB Color Readings**		
			L*	a*	b*
Basic Cotton Ultra	Dry Crocking	Green	60.6084	-26.2889	42.7140
		Blue	30.4446	-3.9094	-33.4180
		Red	48.5852	50.9510	46.7198
Kona® Cotton		Green	55.6389	-29.8739	43.4283
		Blue	29.1990	-4.2535	-33.3400
		Red	46.3818	50.9768	46.2750
Cotton Lawn Ultra		Green	58.5151	-25.5816	43.9401
		Blue	26.7486	-0.6142	-31.3115
		Red	46.9004	51.4993	46.7409
Basic Cotton Ultra	Wet Crocking	Green	59.9981	-26.0972	42.2697
		Blue	30.6832	-4.0217	-33.4078
		Red	49.0216	47.7067	40.3551
Kona® Cotton		Green	55.8011	-30.3194	44.1430
		Blue	29.9384	-4.2142	-32.7280
		Red	46.6767	50.9506	46.0225
Cotton Lawn Ultra		Green	58.5102	-24.2861	41.4086
		Blue	28.1950	-0.6627	-29.8663
		Red	47.9790	49.4818	41.9503

Lightfastness

Three, 2”x6,” Kona® Cotton (n=1), Cotton Lawn Ultra (n=1), and basic cotton (n=1) samples, digitally printed with pigment inks, were tested using the AATCC test method 16.3-2012, colorfastness to light: Xenon-Arc, option 3, Xenon-Arc lamp, continuous light, black panel option. The digitally printed pigment samples were tested for colorfastness to light and the ΔE* color changes were obtained in Table 4.21.

Table 4.21. *ΔE* Color Change of Digitally Printed Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton.*

Test	Colors	Basic Cotton Ultra ΔE*	Kona® Cotton ΔE*	Cotton Lawn Ultra ΔE*
Lightfastness	Green	.63	.76	.46
	Blue	1.02	1.72	.52
	Red	.26	1.43	.39

Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton ΔE* Results. Light had little to no impact on the color of the samples with all color changes being under 2. Cotton lawn had the lowest ΔE* color change.

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. The change in color using the grey scale for colorfastness to light is shown in Table 4.22.

Table 4.22. *Change in Color and Staining of Digitally Printed Pigment Samples for Dry & Wet Crocking Test*

Cotton Fabrication	Hue	Change In Color (Gray Scale Grade)
Basic Cotton Ultra	Green	5
	Blue	5
	Red	5

Table 4.22 (continued)

Kona® Cotton	Green	5
	Blue	5
	Red	5
Cotton Lawn Ultra	Green	5
	Blue	5
	Red	5

The pigment samples had excellent colorfastness to light. There is no visual difference or change in color of any pigment sample. The CIELAB colors are reported in Table 4.23 and the results are consistent with the other lightfastness color tests.

Table 4.23. *CIELAB Color Strength of Digitally Printed Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton*

Cotton Fabrication	**Test**		**CIELAB Color Readings**		
			L*	**a***	**b***
Basic Cotton Ultra	Light-fastness	Green	60.6410	-26.9714	43.7065
		Blue	30.4159	-4.0662	-32.6702
		Red	48.6160	50.8694	46.9873
Kona® Cotton		Green	56.1111	-31.1553	44.7309
		Blue	29.2898	-4.2682	-33.5538
		Red	46.8709	52.0251	47.3564
Cotton Lawn Ultra		Green	58.8624	-25.9448	43.8324
		Blue	26.9653	-1.0366	-31.3638
		Red	47.5187	52.5278	47.8962

CIELAB Colorfastness Results. Very little change happened in the CIELAB color during the lightfastness test. It can be concluded that digitally printed, pigment samples have very excellent colorfastness to light.

Perspiration

Using the acid perspiration solution from Table 4.8, the digitally printed pigment samples were tested for colorfastness to perspiration and reported the ΔE* color change in Table 4.24.

Table 4.24. *ΔE* Color Change of Digitally Printed Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton.*

Test	Hue	Basic Cotton Ultra ΔE*	Kona® Cotton ΔE*	Cotton Lawn Ultra ΔE*
Perspiration	Green	2.25	1.13	1.21
	Blue	1.18	2.32	.46
	Red	.62	1.05	1.35

Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton ΔE* Results . The Basic Cotton Ultra green sample had the largest color change at 2.25. The perspiration solution did not have an immense impact on the color of the pigment samples.

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. With very little impact perspiration had on the digitally printed pigment samples, there was no apparent change in color using the gray scale as seen in Table 4.25.

Table 4.25 *Change in Color and Staining Of Digitally Printed Pigment Samples for Dry & Wet Crocking Test*

Cotton Fabrication	Hue	Change In Color (Gray Scale Grade)	Staining (9 Step*)
Basic Cotton Ultra	Green	5	5
	Blue	5	5
	Red	5	5
Kona® Cotton	Green	5	5

Table 4.25 (continued)

	Blue	5	5
	Red	5	5
Cotton Lawn Ultra	Green	5	5
	Blue	5	5
	Red	5	5

All change in color ratings were a 5, meaning there was no visible difference in the tested samples. There was no visible staining that occurred on the multi-fiber test cloth with all samples obtaining ratings of a 5.

CIELAB Colorfastness Results. In Table 4.26 the CIELAB color reported for the perspiration test for pigment inks reported very little color difference.

Table 4.26. *CIELAB Color Strength of Digitally Printed Pigment Kona® Cotton, Cotton Lawn Ultra, and Basic Cotton*

Cotton Fabrication		**CIELAB Color Readings**		
		L*	**a***	**b***
Basic Cotton Ultra	Perspiration	Green	58.3866	-24.9206
		Blue	29.9713	-3.8450
		Red	47.9773	50.2049
Kona® Cotton		Green	55.1768	-29.7873
		Blue	29.4897	-4.2246
		Red	46.3022	50.0150
Cotton Lawn Ultra		Green	57.7461	-25.4109
		Blue	26.8280	-0.7909
		Red	46.7757	51.5331

The Basic Cotton Ultra, again, had the strongest LAB colors while Kona® Cotton produced the dullest of the 3 colors. All colors are strong and intense with minimal difference between them.

The ΔE* color change for both reactive and pigment sateen and twill varied from test to test. To visually see the difference between each test, the data was made into a bar graph. Refer to Figure A3 Basic Cotton Ultra, A4 Kona® Cotton, and A5 Cotton Lawn Ultra to visually see the difference in ΔE* for each test.

Colorfastness Difference between Reactive Samples

All other reactive samples, cotton percale, cotton duck, and cotton canvas, printed at Iowa State University using a Mimaki TX2-1600 digital textile printer, were tested for colorfastness to laundering, crocking, perspiration, and light. All of the reactive samples were compared to each other by the ΔE* color change value, Gray Scale for Evaluating Change in Color rating, 9 Step Chromatic Transference Scale rating, and CIELAB value. The goal of these experiments was to understand the feasibility of reactive inks on natural fibers in a variety of conditions in which they may be used.

Laundering

Fifteen, 2”x6,” cotton percale (n=5), cotton duck (n=5), and cotton canvas (n=5) samples, digitally printed with pigment inks, were tested using the AATCC standard Colorfastness to Laundering: Accelerated, test method 61-2013 as seen in Table 4.27.

Table 4.27. *ΔE* Color Change of Digitally Printed Reactive Cotton Percale, Duck, and Canvas*

Wash	Hues	Percale ΔE*	Duck ΔE*	Canvas ΔE*
A1	Green	4.21	3.53	6.48
	Blue	6.58	5.1	6.48

Table 4.27 (continued)

	Red	8.43	4.32	6.76
A2	Green	3.97	5.83	7.04
	Blue	7.14	5.72	5.13
	Red	8.21	5.73	7.91
A3	Green	7.43	4.06	4.87
	Blue	5.54	6.25	5.43
	Red	7.53	13.13	9.88
A4	Green	6.17	5.28	4.69
	Blue	6.77	5.88	4.86
	Red	8.66	8.18	7.04
A5	Green	3.83	7.27	5.59
	Blue	7.85	5.03	5.97
	Red	8.61	6.44	5.90

Cotton Percale, Cotton Duck, and Cotton Canvas ΔE* Results . Cotton percale, duck, and canvas all lost a substantial amount of color during the laundering process. The color red perceivably had a greater color loss than the colors blue and green. There was not one wash that produced better or worse results than another; each fabric was affected differently. For cotton percale and cotton duck, wash A1 produced the best results. This wash consisted of a high volume of water, low agitation, and a larger amount of detergent. Cotton canvas lost the least amount of color during wash A5, which consisted of an average amount of water, agitation, and detergent and a small amount of bleach. Cotton duck red had the most color loss of all color samples at ΔE* 13.13. Overall, reactive inks do not have a good colorfastness to laundering. Figure 4.8 shows the best and worst laundering results of reactive cotton percale, Figure 4.9 shows cotton duck samples, and Figure 4.10 shows cotton canvas samples.

Figure 4.8 Best, worst, & original reactive cotton percale samples

Figure 4.9 Best, worst, & original reactive cotton duck samples

Figure 4.10 Best, worst, & original reactive cotton canvas samples

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. The AATCC gray scale and 9-step chromatic transference scale were used to obtain color change and staining ratings seen in table 4.28.

Table 4.28. *Change in Color and Staining of Digitally Printed Reactive Cotton Percale, Duck, and Canvas.*

Cotton Fabric	**Wash**	**Change in Color (Gray Scale Grade)**			**Staining (9 Step*)**
		Green	Blue	Red	
Percale	A1	3-4	3	3	4
Duck	A1	4-5	4	4	3.5
Canvas	A1	4	3-4	3	4.5
Percale	A2	3-4	4	4	3.5
Duck	A2	4-5	4-5	4-5	4.5
Canvas	A2	4	3-4	3-4	4.5
Percale	A3	3	3	3-	1.5
Duck	A3	4-5	4	4	2
Canvas	A3	4-5	4	4	1.5
Percale	A4	3	3	3	1.5
Duck	A4	4-5	4-5	4-5	2
Canvas	A4	4	4	4	2.5
Percale	A5	3	3	3	3.5
Duck	A5	4-5	4-5	4-5	3
Canvas	A5	4-5	4-5	4-5	5

According to the gray scale grade, wash A1 slightly produced the best washing results. All laundering tests produced similarly the same results, which is consistent with Table 4.25. Each multi-fiber test strip was tested for staining according to the 9-step chromatic transference scale. The most staining occurred for all fabrics during wash A3. All results were below a 2 meaning an excessive amount of staining occurred. The least amount of staining happened during wash A2. Overall, the reactive inks do not withstand laundering very well.

CIELAB Colorfastness Results. The color readings from the CIELAB colors from the spectrophotometer, in Table 4.29, support the findings obtained by the ΔE* color change, gray scale, and 9-step chromatic transference scale.

Table 4.29. *CIELAB Color Strength of Digitally Printed Reactive Ink Cotton Percale, Duck, and Canvas Samples*

Cotton Fabrication	**Wash**	**Hue**	**CIELAB Color Readings**		
			L*	a*	b*
Percale	A1	Green	54.5182	-28.1519	25.6750
		Blue	33.0045	-1.1239	-22.9345
		Red	46.7703	38.8792	30.4677
Duck	A1	Green	44.6661	-36.5429	19.9054
		Blue	22.1630	0.6225	-27.6171
		Red	39.7530	45.5991	29.0371
Canvas	A1	Green	46.7921	-33.6523	17.5357
		Blue	33.8424	-19.2289	-26.3893
		Red	49.1668	30.9434	34.4445
Percale	A2	Green	55.4958	-28.2850	-28.2850
		Blue	33.5087	-1.7262	-23.4536
		Red	46.3784	38.9539	30.7918
Duck	A2	Green	45.8483	-35.0710	18.8976
		Blue	22.5798	1.1511	-26.9824
		Red	40.6046	45.6312	29.4367
Canvas	A2	Green	46.7521	-34.5960	17.9076
		Blue	33.7178	-20.2273	-26.9098
		Red	49.7136	31.1268	34.1850
Percale	A3	Green	51.9528	-24.8190	22.7893

Table 4.29 (continued)

		Blue	31.8191	-0.8836	-22.8643
		Red	44.5315	36.1018	28.1156
Duck	A3	Green	44.6958	-31.8091	17.8937
		Blue	23.7167	0.6408	-24.7922
		Red	38.1171	40.0321	25.0581
Canvas	A3	Green	44.6435	-33.4102	15.2839
		Blue	33.5361	-18.0460	-24.6304
		Red	47.0853	28.4790	30.9803
Percale	A4	Green	52.3077	-25.4906	23.5658
		Blue	33.2769	-0.1383	-21.8950
		Red	44.7196	34.9999	27.5089
Duck	A4	Green	43.6503	-33.8278	18.0415
		Blue	22.2203	1.9533	-27.2257
		Red	38.4958	41.7185	26.3180
Canvas	A4	Green	45.8872	-32.8783	16.6976
		Blue	32.7243	-19.3774	-26.3515
		Red	47.5426	30.1301	32.6397
Percale	A5	Green	54.4332	-27.2168	25.1652
		Blue	34.0935	-0.8868	-22.3685
		Red	46.6354	37.0673	28.3741
Duck	A5	Green	45.5591	-35.5018	18.4591
		Blue	21.8214	1.0695	-27.5843
		Red	39.5733	44.9463	27.5547
Canvas	A5	Green	45.9161	-35.9111	16.5637
		Blue	32.4793	-19.1776	-27.8627
		Red	48.0241	30.4818	33.3412

The CIELAB results were consistent with those of Tables 4.25 and 4.26. Test A3 resulted in less intense colors and test A1 resulted in the most intense colors out of all the samples.

Crocking

Nine, 2”x6,” cotton percale (n=3), cotton duck (n=3), and cotton canvas (n=3) samples, digitally printed with reactive inks, were tested for crocking in accordance to the AATCC test method 8-2013 crockmeter method.

Cotton Percale, Cotton Duck, and Cotton Canvas ΔE* Results. A dry crocking and wet crocking test was conducted on all reactive samples and the ΔE* color change was reported in Table 4.30.

Table 4.30. *ΔE* Color Change of Digitally Printed Reactive Cotton Percale, Duck, and Canvas.*

Test	Hues	Percale ΔE*	Duck ΔE*	Canvas ΔE*
Dry Crocking	Green	3.09	1.28	1.16
	Blue	.88	3.45	1.03
	Red	1.54	1.69	1.6
Wet Crocking	Green	3.00	1.03	1.52
	Blue	.31	.85	1.04
	Red	2.64	1.7	.57

Cotton canvas produced the overall best washing results having the lowest ΔE* color change. The difference in color between wet and dry crocking was not substantial, with both tests producing around the same results. The worst color change occurred from the cotton duck dry crocking.

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. Using the gray scale and 9-step chromatic transference scale the color change and staining all obtained a rating in Table 4.31.

Table 4.31. *Change in Color and Staining of Digitally Printed Reactive Cotton Percale, Duck, and Canvas.*

Cotton Fabrication	Hues	Dry Crocking - Change in Color (Gray Scale Grade)	Dry Crocking - Staining (9-Step*)	Wet Crocking Change in Color (Gray Scale Grade)	Wet Crocking - Staining (9-Step*)
Percale	Green	4	4.5	4	2
	Blue	4	4	4	1.5
	Red	4-5	4.5	4	2
Duck	Green	4-5	3	4	2
	Blue	3	1	3-4	1.5

Table 4.31 (continued)

	Red	4	2	4	1.5
Canvas	Green	4-5	4	4	2.5
	Blue	4-5	4	4	2.5
	Red	4	4.5	4	3.5

The highest ratings obtained were for cotton canvas from both wet and dry crocking. Cotton duck obtained the worst ratings having the most visible difference in color. 16 of the 18 color change ratings were above a 4 meaning that there is visible color difference but nothing substantial. The worst rating for color change was a 3 and was cotton duck blue. Substantial staining occurred during wet crocking with only slight staining occurring during dry crocking. The excessive staining during wet crocking may likely ~~to~~ occur because the reactive inks that did not get fixed during the post-process treatment are more likely to transfer ink when wet.

CIELAB Colorfastness Results. The results of the CIELAB colors in Table 4.32 are consistent with both other crocking test results.

Table 4.32. *CIELAB Color Strength of Digitally Printed Reactive Ink Cotton Percale, Duck, and Canvas Samples*

Cotton Fabrication	**Test**	**Hue**	**CIELAB Color Readings**		
			L*	**a***	**b***
Percale	Dry Crocking	Green	51.4690	-30.3115	25.0965
		Blue	27.8897	-1.1635	-23.8055
		Red	41.3849	42.5908	29.2676
Duck		Green	43.5111	-36.2202	19.6465
		Blue	21.2530	0.3175	-26.3099
		Red	37.0973	48.0073	32.0109
Canvas		Green	43.5418	-35.4340	13.5228
		Blue	30.4518	-22.1951	-27.7815
		Red	48.6158	35.7949	34.9316
Percale	Wet Crocking	Green	52.9389	-28.8178	27.4710
		Blue	28.6218	-0.5123	-23.7763

Table 4.32 (continued)

	Red	41.4201	41.0444	27.8132
Duck	Green	43.0462	-36.8187	21.5429
	Blue	19.7661	1.1704	-26.4740
	Red	36.9934	48.1610	31.5058
Canvas	Green	44.3469	-35.4340	15.3218
	Blue	30.6638	-19.2151	-26.6615
	Red	47.8168	32.7659	32.9416

Lightfastness

Three, 2”x6,” cotton percale (n=1), cotton duck (n=1), and cotton canvas (n=1) samples, digitally printed with pigment inks, were tested using the AATCC test method 16.3-2012, colorfastness to light: Xenon-Arc, option 3, Xenon-Arc lamp, continuous light, black panel option. The ΔE* color changes were obtained and recorded in Table 4.31.

Cotton Percale, Cotton Duck, and Cotton Canvas ΔE* Results . Light has a very small effect on the cotton percale, duck, and canvas, as recorded in Table 4.33.

Table 4.33. *ΔE* Color Change of Digitally Printed Reactive Cotton Percale, Duck, and Canvas*

Test	Hues	Percale ΔE*	Duck ΔE*	Canvas ΔE*
Lightfastness	Green	2.75	.66	2.25
	Blue	1.4	.85	1.52
	Red	5.77	1.4	1.35

Light had the largest impact on cotton percale with the color red having the largest color loss at 5.77. Cotton duck saw little to no impact on the color change with all ratings under a 1.

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. The gray scale ratings were consistent with the ΔE* color change in table 4.34. Using the gray scale, the cotton percale ratings were the worst of the three fabrics, all obtaining ratings of 4. All ratings were a 4 or above meaning there is little to no visible color change occurring.

Table 4.34 *Change in Color and Staining of Digitally Printed Reactive Cotton Percale, Duck, and Canvas.*

Cotton Fabrication	**Hues**	**Change in Color (Gray Scale Grade)**
Percale	Green	4
	Blue	4
	Red	4
Duck	Green	5
	Blue	4-5
	Red	4-5
Canvas	Green	4-5
	Blue	4
	Red	4

CIELAB Colorfastness Results. The CIELAB color readings obtained for cotton percale, duck, and canvas in Table 4.35 are consistent with the findings in Tables 4.33 and 4.34. There is very little difference in the color readings from the lightfastness test. Digitally printed reactive samples had excellent colorfastness to light.

Table 4.35. *CIELAB Color Strength of Digitally Printed Reactive Ink Cotton Percale, Duck, and Canvas Sample***s**

Cotton Fabrication	**Test**	**Hue**	**CIELAB Color Readings**		
			L*	a*	b*
Percale	Light-fastness	Green	51.9890	28.6642	25.7578
		Blue	28.7707	-0.1783	-22.7354
		Red	41.0436	37.0425	26.2200
Duck		Green	42.4273	-36.8554	21.4600
		Blue	19.0500	0.2565	-26.3239
		Red	36.7744	47.5351	31.2947
Canvas		Green	42.1147	-31.7828	12.5226
		Blue	30.3227	-2.5562	-27.1425
		Red	48.2470	34.3747	33.5366

Perspiration

Using the acid perspiration solution from Table 4.8, the digitally printed pigment samples were tested for colorfastness to perspiration and the ΔE* color results were reported in Table 4.36.

Table 4.36. *ΔE* Color Change of Digitally Printed Reactive Cotton Percale, Duck, and Canvas*

Test	Hues	Percale ΔE*	Duck ΔE*	Canvas ΔE*
Perspiration	Green	12.24	11.78	13.79
	Blue	11.27	10.39	14.13
	Red	6.28	7.89	13.76

Cotton Percale, Cotton Duck, and Cotton Canvas ΔE* Results. Digitally printed reactive cotton percale, duck, and canvas all experience a large amount of color loss when in contact with perspiration. The cotton canvas experienced the largest color loss. All but two color ratings were above a 10 meaning there is a substantial difference in color that happens during perspiration.

Gray Scale Ratings Results & 9-Step Chromatic Transference Scale. Table 4.37 contains the change in color and staining ratings for cotton percale, duck, and canvas. The ratings were consistent with the ΔE* color change. The cotton canvas obtained ratings of 3 and below having the worst change in color. However, the cotton percale and cotton duck obtained mainly 3 ratings meaning they also experienced a moderate and noticeable color difference. Moderate but not substantial staining occurred to the test swatch during perspiration. The worst staining occurred for cotton duck and the least staining occurred for cotton percale.

Table 4.37. *Change in Color and Staining of Digitally Printed Reactive Cotton Percale, Duck, and Canvas*

Cotton Fabrication	Hue	Change in Color (Gray Scale Grade)	Staining (9 Step*)
Percale	Green	4	4.5
	Blue	3	3
	Red	3-4	4.5
Duck	Green	3-4	3.5
	Blue	3	3
	Red	3	3
Canvas	Green	3	3.5
	Blue	2	3.5
	Red	2-3	4.5

CIELAB Colorfastness Results. The CIELAB color readings are reported in Table 4.38. The CIELAB colors were consistent with the other findings for the perspiration tests. The results indicate that perspiration has a negative effect on reactive ink cotton fabrics.

Table 4.38. *CIELAB Color Strength of Digitally Printed Reactive Ink Cotton Percale, Duck, and Canvas Samples*

Cotton Fabrication	Test	Hue	CIELAB Color Readings		
			L*	a*	b*
Percale	Perspiration	Green	50.8883	-31.1349	26.1976
		Blue	26.8848	1.9898	-24.5195
		Red	41.3957	45.0753	29.9640
Duck		Green	45.0058	-35.8469	21.7228
		Blue	21.8896	1.4233	-26.7957
		Red	39.7340	47.1500	32.0004
Canvas		Green	45.2548	-36.4465	16.8134
		Blue	31.4468	-21.4849	-27.2375
		Red	49.0061	36.5387	36.2369

The ΔE* color change for both reactive and pigment sateen and twill varied from test to test. To visually see the difference between each test the data was made into a bar graph. Refer to Appendix A figures A8 cotton percale, A9 cotton duck, and A10 cotton canvas to visually see the color difference for each test.

CHAPTER 5. DISCUSSION

Overview of the Performance of Fabrics Digitally Printed with Reactive Inks

The expansion of the digital textile printing industry requires consistent color reproducibility on textiles with excellent colorfastness. Digitally printed woven cotton fabrics printed with pigment and reactive inks were tested and analyzed to determine colorfastness to laundering, perspiration, crocking, and light. In this study, the colorfastness performance reactive inks were worse than pigment inks in the areas of colorfastness to light, crocking, laundering, and perspiration. From the results of the colorfastness tests, recommendations were made for appropriate and inappropriate uses for each woven cotton fabrication tested. The reactive inks performed worse than pigment inks and experienced the most color loss during perspiration and laundering. Recommendations were made for appropriate uses and conditions for each fabric type.

Cotton Twill

Cotton twill fabrics printed with reactive inks have a tendency to lose an excessive amount of color during the laundering process. Washing a cotton twill garment daily will have a large negative impact on the color of the garment over time, resulting in a significant loss of color in the garment. Submerging cotton twill in a small amount of water with higher agitation and less detergent produced the worst results for color in the laundering test. With this same combination of conditions, moderate to severe staining occurs on adjacent fabrics being washed with the cotton twill. *Therefore, it is recommended to wash cotton twill fabrics that have been digitally printed with reactive inks- in a higher volume of water, less* *agitation, and extra detergent to produce the best color results.* This will produce a better color retention outcome and less staining to other garments and fabrics in the same wash cycle. Printing cotton twill fabrics with reactive inks is not a fabric-ink combination that would be recommend for clothing such as children's wear, uniforms, or every-day, ready-to-wear, clothing.

In addition, a cotton twill-reactive ink combination is also not recommended for fabrics that come in contact with perspiration. The overall color of the cotton twill-reactive ink sample changed significantly, with color bleeding occurring when in contact with perspiration. Moderate staining also occurred to the adjacent fabric. Cotton twill printed with reactive inks is not recommended for athletic clothing. The wearer may experience bleeding of colors and transfers of staining to an under or over shirt.

Dry crocking, or the rubbing of one dry fabric to another dry fabric, has a moderate impact on the cotton twill with reactive ink. There may be a slight color difference visible on the fabric, but it will not b~~e~~ significant. If the reactive ink printed fabric is being rubbed against another fabric, the other fabric will experience a slight stain, with color from the printed fabric transferring to the adjacent fabric.

Wet crocking, or the rubbing of a wet fabric against a dry fabric, has more of an impact on staining than on color change. There will only be a slight visible difference in the printed fabric after crocking. The staining of the adjacent fabric, however, will show a significant amount of color. This is the color that is transferred from the printed fabric to an unprinted, plain, fabric.

Light does not have a large color loss impact on the cotton twill reactive fabric. There will be a very slight difference in color after exposure to light, but nothing major over a long period of time. Garments that may be in a gallery or museum with constant lighting would not lose an excessive amount of color over time.

Cotton Sateen

Cotton sateen printed with reactive inks may lose a moderate amount of ink during the laundering process. The loss will not be excessive, but it will be significant enough to visually see the difference. It will take multiple washes to see a significant difference of color in the fabric. Cotton sateen printed with reactive inks would not be suitable for clothing such as children's wear that needs to be washed daily. A more appropriate use would be for home goods or jackets and scarves, which typically do not need to be washed daily. *The best laundering conditions would be to wash the cotton sateen fabric digitally printed with reactive inks in a high volume of water with less agitation and more detergent*. Slight staining may occur to other garments being washed with the cotton sateen.

Garments made out of cotton sateen using reactive inks are *not* recommended for wear during activities, which generate heavy perspiration. . Small amounts of perspiration will not change the color of the garments drastically. While there is not an excessive amount of color loss, there still is a slight color loss, which is visible after perspiration.

A small amount of color may transfer to any adjacent fabrics and cause slight staining. Garments and home goods that crock, or rub, against other surfaces will not create a huge problem unless the cotton sateen fabric is damp or wet.

The dry crocking has a very slight impact on the overall color of the fabric and causes very little staining to adjacent fabrics. Wet crocking, however, leaves excessive staining of color to adjacent fabrics. Light exposure has little to no impact on the cotton sateen reactive fabric. Therefore, it could be useful for signage or banners, preferably in an indoor situation. The banners will sustain their color over a long period of time exposed to light.

Cotton Percale

Cotton percale printed with reactive inks does not produce an over-all bright, vibrant, color. Adding bleach to the laundry bath and high agitation can negatively affect the color outcome. The staining of adjacent fabrics can also be severe from the color loss of the percale fabric during strong agitation during laundering. *The best laundering conditions for cotton percale fabric digitally printed with reactive inks is to wash them in a high volume of water with less agitation and more detergent*. During this laundering combination minimal staining will occur to other garments in the same laundry bath. Producing dull colors and losing color during laundering is why cotton percale printed with reactive inks would *not* be an appropriate choice for every day, ready-to-wear, clothing.

Cotton percale also does not withstand perspiration very well. Perspiration causes a slightly above moderate change to the color and a moderate staining to adjacent fabrics. The print design tends to bleed as well making cotton percale not an ideal fabric to create sportswear with.

Dry crocking and wet crocking had the same effect on the color change of the cotton percale fabric. Both caused a moderate change in color, meaning it was enough to be noticeable, but not severe. The severity is in the staining during wet crocking. A significant amount of color will be transferred to adjacent fabrics that the wet cotton percale rubs against.

Light does not have a noticeable effect on the color of cotton percale. It is recommended that the cotton percale does not spend an excessive amount of time exposed to light, as over time the colors will start to fade. An acceptable use would be for a gallery or museum garment display since constant lighting will not have an immense impact on the overall color.

Cotton Duck

Cotton duck printed with reactive inks results in a nice, bright, vivid color that that has a moderate colorfastness to laundering. *Cotton duck printed with reactive inks should be washed in a high volume of water with less agitation and more detergent.* Little staining will occur on adjacent fabrics and garments during this washing process. It is not recommended to add bleach during the laundering process, as it will increase the color loss, as well. Excessive staining will occur to adjacent fabrics and garments during a high agitation wash, as well.

Cotton duck printed with reactive inks is not an ideal fabric for garments that will be exposed to sweat while wearing. Perspiration will result in bleeding of the color and a moderate amount of color loss. Perspiration also allows for the colors to bleed and stain adjacent garments, such as an under or over shirt.

Crocking, or rubbing against other fabrics, will not have an overall, large, impact on the color of the cotton duck, but may have a negative impact on the adjacent garments or fabric. Staining is likely to occur during rubbing and can cause an excessive amount of color transfer from the cotton duck to the adjacent fabrics. The same amount of staining will occur whether dry crocking or wet crocking is happening. Cotton duck is suitable for light jackets that may not need to be washed daily and that would not experience a large amount of crocking. Tote bags or backpacks that do not experience heavy abrasion would be ideal products to be made out of cotton duck.

Light does not have any impact on the color of the cotton duck. It would take excessive amount of light exposure to visually see a significant difference in the color.

Cotton Canvas

In general**,** cotton canvas printed with reactive inks in results in colors that are not bright and vivid.. An even amount of color is lost from the cotton canvas whether it is washed in a low volume of water with little agitation or high volume of water with high agitation. *It is recommended for cotton canvas digitally printed with reactive inks to be washed in a moderate amount of water with a larger amount of detergent and low agitation*. A small amount of bleach, in this case, will not have a negative effect on the color but rather, will actually help the color.

Cotton canvas would not be ideal for clothing, especially children's wear that may need washing daily. Perspiration has a negative effect on the colors in cotton canvas. Bleeding will occur and color loss will happen. Slight staining will also occur to adjacent fabrics. Cotton canvas is not an ideal fabric for garments. Not only will it be uncomfortable, but also it does not hold a bright, vivid, color and will experience color loss during laundering and exposure to perspiration.

Cotton canvas printed with reactive inks will not experience a substantial color loss during crocking. Dry crocking will show little to no visual difference and little staining will occur to adjacent fabrics. Wet crocking will show slightly more visual difference in color and moderate staining will occur to the adjacent fabrics.

Light will have little impact on the overall color of the cotton canvas and can withstand a large amount of time exposed to light. The proper use for cotton canvas is signage and banners and as stated previously, is not recommended for apparel.

Suggested Reactive Ink Uses for Various Digitally Printed Cotton Fabrications

Reactive inks are more suitable for some products than others and perform better under certain conditions. Table 5.1 explores five cotton fabrics printed with reactive inks and their recommended uses, as well as uses that are not recommended for the particular fabrics.

Table. 5.1 *Suggested Reactive Ink Uses for Various Cotton Fabrications*

Fabrications	Appropriate Use	Examples of Appropriate Use	Inappropriate Use	Examples Inappropriate Use
Cotton Twill	• Conditions of light	• Home goods not with	• Conditions of abrasion	• Fashion apparel,

Table 5.1 (continued)

	exposure	much abrasion (i.e. draperies)	• Conditions of moisture or perspiration • Items that need daily laundering care	everyday garments • Children's wear • Home goods that have abrasion or high laundering needs (i.e. pillows, upholstery)
Cotton Sateen	• Conditions of light abrasion • Conditions of light exposure	• Home goods not exposed to water • Indoor signage • Garments not needing daily laundering	• Items that need excessive laundering • Conditions of excessive perspiration	• Children's wear • Everyday garments • Accessories (i.e. scarves, headbands)
Cotton Percale	• Conditions of light abrasion • Condition of light exposure	• Home goods	• Items that need daily laundering • Conditions of perspiration	• Fashion apparel, everyday garments • Children's wear • Home goods that have abrasion or high laundering needs (i.e. pillows, upholstery) • Accessories (i.e. scarves, headbands)
Cotton Duck	• Conditions of gentle cycle laundering • Conditions of light abrasion • Conditions of light exposure	• Home goods not exposed to water • Jackets • Tote bags	• Conditions of wet, heavy, abrasion • Conditions of perspiration	• Fashion apparel, everyday garments • Children's wear

Table 5.1 (continued)

Cotton Canvas	• Conditions of light abrasion • Condition of light exposure	• Home goods • Signage & banners	• Items that need excessive laundering • Conditions of wet, heavy, abrasion • Conditions of perspiration	• Fashion apparel, everyday garments • Children's wear • Home goods that have abrasion or high laundering needs (i.e. pillows, upholstery)

Overview of the Performance of Fabrics Digitally Printed with Pigment Inks

Pigment inks, overall, have an excellent colorfastness to laundering, crocking, light, and perspiration. Each cotton fabric showed slightly different results for each test but it was concluded that pigment inks are the more successful inks to print with. Brighter, more vivid colors were a result of the pigment inks after all tests were conducted.

Cotton Twill

The cotton-twill pigment-ink combination resulted in overall bright, vibrant, beautiful, colors. The amount of color lost during laundering of the cotton twill with pigment ink depends on the type of laundering process. Overall, there was no extreme color loss during any laundering cycle. Washing the cotton twill with little water and high agitation with a small amount of detergent -resulted in the most color loss. However, the color loss is still considered a moderate amount and is nothing substantial. *To achieve little to no color loss, the best laundering* *recommendation is to wash the cotton twill fabric in a high volume of water, low agitation, and more detergent.*

Cotton twill experiences very little color loss when in contact with perspiration. Even though cotton twill may not be a fabrication ideally used in perspiration settings, if sweated in, there will be little to no affect. There will also be no color staining that is transferred to any adjacent fabric during perspiration.

Both wet and dry crocking have little impact on the overall color of cotton twill printed with pigment inks. A slight visible color change may occur but the color loss will not be substantial. The only issue that arises with crocking is the color transferred to adjacent fabrics. The same amount of staining occurs for both wet and dry crocking and some staining is classified as substantial. Therefore, even though there is little color difference in the fabric, the staining to adjacent fabrics may be excessive.

Light has very little impact on cotton twill printed with pigment inks. The color in the cotton twill should be able to withstand a substantial period of time exposed to sunlight. It is recommended that cotton twill printed with pigment inks be used for home goods that will not transfer staining to adjacent fabrics, jackets that do not need laundered daily, tote bags, backpacks, and banners and signage.

Cotton Sateen

Cotton sateen printed with pigment inks will lose a small to moderate amount of color during the laundering process. Washing cotton sateen in little water and detergent with high agitation will result in an excessive amount of color loss, much more substantial than any other laundering process. *It is recommended to* *wash cotton sateen printed with pigment inks in moderate to high volume of water, with more detergent to produce the best color results.* Little to no staining will occur to adjacent fabrics or garments in the same laundering cycle.

The result of perspiration on cotton sateen printed with pigment inks showed little to no color loss. Cotton sateen has great colorfastness to perspiration and minimal bleeding and color loss will occur. There will be no staining to adjacent fabrics, as well. It is safe to do athletic activity while wearing cotton sateen garments, such as warm up shirts, light jackets or pants without worry that there may be color loss or color transfer.

Minimal visual difference in color will occur during wet and dry crocking. A very slight color loss may occur but it may be so subtle that it is not noticeably visible. Moderate staining will occur to adjacent fabrics, which the cotton sateen may be rubbing against.

Additionally, exposure to light will not be an issue with cotton sateen pigment fabrics. Cotton sateen will be able to withstand a substantial amount of time exposed to light before any visible color loss. Cotton sateen printed with pigment inks would be ideal for shirting, dresses, accessories such as scarves, as well as signage and banners, home goods, and quilting.

Basic Cotton Ultra

Basic Cotton Ultra printed with pigment inks has excellent wash fastness. The color loss during laundering is very minimal. The most substantial color loss the Basic Cotton Ultra experienced was during a wash with a low volume of water, high agitation, and minimal detergent. This color loss, however, was less than moderate.

Any washing in a moderate to high volume of water, with more detergent and less agitation will produce little to no visible color difference in the Basic Cotton Ultra.

Perspiration also has little to no effect on the Basic Cotton Ultra. There will be minimal color loss, not noticeably visible to the fabric. No staining is likely to occur to adjacent fabrics or garments during perspiration.

Basic Cotton Ultra resulted in similar color loss during wet and dry crocking, both of which were minimal. The staining that occurs to the adjacent fabrics is much more substantial than the color loss of the original fabric. Moderate to severe staining is expected during both wet and dry crocking.

Light is not an issue for loss of color for Basic Cotton Ultra. Basic Cotton Ultra will be able to withstand a substantial amount of time exposed to light before an affect it seen. Basic Cotton Ultra would be ideal for clothing such as shirting, dresses, and children's dress clothing. It is also ideal for accessories such as scarves and headbands, home goods, linens, quilting, and banners and signage.

Kona® Cotton

The colorfastness of Kona® Cotton is dependent on the laundering process. A moderate color loss may happen when lowering the amount of water and raising the amount of agitation during the wash. Garments that can be washed on a delicate cycle would be ideal for Kona® Cotton. *The recommended washing process is to wash the fabric in a high volume of water, low agitation, and more detergent.*

The amount of crocking for Kona® Cotton was dependent on the colors. Some colors experienced worse crocking than other. The overall crocking for both wet and dry was moderate to low. Moderate staining is likely for adjacent fabrics or garments the Kona® Cotton is rubbing against.

Perspiration has little effect on the overall color of Kona® Cotton. There will be no significant color loss as well as little staining occurring to any adjacent fabrics. Along with perspiration, light exposure also will not have a large impact on the overall color. Kona® Cotton should be able to withstand exposure to light for a significant amount of time without experiencing visible color loss.

Kona® Cotton is a suitable fabric for clothing such as dresses and shirting. It is not recommended for children's wear because they typically require strong washes to remove dirt and stains. Kona® Cotton performs better in a gentle cycle. It can also be used for home goods, linens, quilting, and accessories, such as scarves and headbands.

Cotton Lawn Ultra

Cotton Lawn Ultra, overall, experienced moderate loss during the laundering process. As the amount of water decreases and the agitation increases, Cotton Lawn Ultra will experience more color loss and adjacent fabrics experienced more color staining. Adding bleach to the laundry bath is also not recommended as it may even double the amount of color loss. *The recommended washing process is to wash the fabric in a high volume of water, low agitation, and more detergent which will result in only losing a very minimal amount of color.*

Wet and dry crocking affects Cotton Lawn Ultra differently. More color loss will happen during wet crocking than dry crocking. The amount of staining that occurs to adjacent fabrics is similar for both types of crocking.

Perspiration and light did not have enough of an impact on the fabric to visually see a color loss. No staining occurred to adjacent fabrics during perspiration as well. Cotton Lawn Ultra will only start to experience color loss from exposure to light if exposed to it for a very substantial amount of time. Cotton Lawn Ultra is an ideal fabric for lightweight apparel and accessories, home goods, linens, and quilting.

Pigment Ink Uses for Various Cotton Fabrications

Pigment inks, overall, have great colorfastness. Table 5.1 explores five cotton fabrics printed with pigment inks and their recommended uses, conditions, and uses not recommended.

Table. 5.2. *Suggested Reactive Ink Uses for Various Cotton Fabrications*

Fabrications	**Appropriate Use**	**Examples of Appropriate Use**	**Inappropriate Use**	**Examples of Inappropriate Use**
Cotton Twill	• Conditions of light laundering • Conditions of light abrasion • Conditions of light perspiration • Conditions of light exposure	• Jackets • Home Goods • Signage & banners • Tote bags	• Conditions of heavy & excessive abrasion or laundering	• Children's wear • Everyday garments
Cotton Sateen	• Conditions of light laundering • Conditions of light abrasion • Conditions of perspiration • Conditions of light exposure	• Clothing (i.e. shirting, dresses) • Accessories • Home Goods • Signage & banners • Quilting	• Conditions of heavy & excessive abrasion or laundering	• Children's wear • Linens
Basic Cotton Ultra	• Conditions of laundering • Conditions of	• Clothing (i.e. shirting, dresses,	• Conditions of heavy abrasion	

Table 5.2 (continued)

	light abrasion • Conditions of light exposure • Conditions of light perspiration	children's wear) • Home goods • Linens • Quilting • Banners & signage • Accessories (i.e. scarves, headbands)		
Kona® Cotton	• Conditions of light laundering • Conditions of light abrasion • Conditions of light exposure • Conditions of light perspiration	• Clothing (i.e. shirting, dresses) • Home goods • Linens • Quilting • Banners & Signage • Accessories (i.e. scarves, headbands)	• Conditions of heavy & excessive abrasion or laundering	• Children's wear
Cotton Lawn Ultra	• Conditions of light laundering • Conditions of light abrasion • Conditions of light exposure • Conditions of light perspiration	• Lightweight apparel • Home goods • Linens • Quilting • Accessories (i.e. scarves, headbands)	• Conditions of heavy & excessive abrasion or laundering	• Heavy clothing (i.e. uniforms, jackets)

CHAPTER 6. CONCLUSION

Significance

In this study the researcher investigated the feasibility of reactive and pigment inks of digitally printed textiles via colorfastness testing and color analysis according to the standards in the 2015 AATCC manual. Based on the data collected from the research, there is a significant variability found between the pigment and reactive inks when printed on woven cotton textiles. This knowledge is beneficial for students and faculty in apparel and textile design programs, as well as industry professionals.

With the rapid growth in the digital textile printing industry it is imperative to continually conduct new research. New ink types, fiber technologies, and printing equipment are constantly developed. Quality assurance research must be conducted on various fibers and fabrication to ensure that compatible inks are used in digital textile printing processes for the specified use of the end products.

For example, customers expect the colors in athletic wear to not bleed or stain during perspiration and children's wear to withstand multiple launderings. This research was aimed to help small businesses with digital textile printing fabric and ink choices for the proper colorfastness. Choosing to use an improper fabric with certain ink can negatively affect a company's business. This research will help~~s~~ companies and customers better choose cotton fabrics and printing ink processes more suitable for their end use.

The digital textile printing industry is a rapidly growing industry with numerous career opportunities. With that, the digital textile design industry is moving towards pigment inks, therefore it is important for academia to make this transition, as well. This research helps support the movement for academic institutions to transition into pigment inks. While reactive inks may be suitable for some wearable art pieces created for school projects, in contrast, pigment inks perform best for apparel and have the best colorfastness. This research also helps students with fabrication choices when selecting material for class projects. It helps them understand the appropriate uses for each fabrication and their colorfastness. Academic instruction and experience that relates to current and trending industry standards and procedures will better prepare students for their future in the apparel and textile industries.

Implications

One of the implications is that this study helps academia better understand the importance of digitally printing with pigment-based inks. Not only will the colorfastness be better, but also there are a wider variety of fabrics pigment inks can print on, such as polyester. Since pigment inks do not have to be printed on pre-treated fabric it creates a much cheaper and more feasible process. The pigment inks also have to undergo a much simpler heat fixing process. Overall, investing in a printer with the capabilities of printing with pigment inks will be relevant to the industry, as well as being cheaper.

Future Research

Future research that needs to be conducted is to find the K/S using the Kubelka-Munk theory on the cotton fabrics tested in this study. The Kubelka-Munk theory is the most widely used theory for color prediction of dye mixtures in dyed textiles and K/S represents color depth (Bae, 2007). The equation for finding K/S is as follows: $K/S = (1-R)^2/2R$. K represents the absorption coefficient, S is the scattering coefficient, and R is the reflectance of the dyed fabric. Finding K/S is imperative for determining color strength.

This study could be replicated using knit cotton fabrics or other fiber types such as nylons, silks, synthetic or polyester fabrics. Woven cotton fabrics were specifically chosen for this study, but it would be essential to test all fibers and weave types to determine the colorfastness to laundering, perspiration, light, and crocking for each fabric as well as appropriate end use for digitally printed textiles.

More colorfastness tests could be conducted on the same cotton test samples as well. Perspiration, light, crocking, and laundering were four common tests, as wearers may experience these daily. These samples were also only tested as 2”x6” samples. Constructing these materials into actual garments and conducting wear tests with humans in the target markets or on a sweating mannequin would determine colorfastness of the entire overall garment. These results then could be compared to this current study to assess and confirm the findings.

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APPENDIX A: ΔE* OF PIGMENT AND REACTIVE INKS

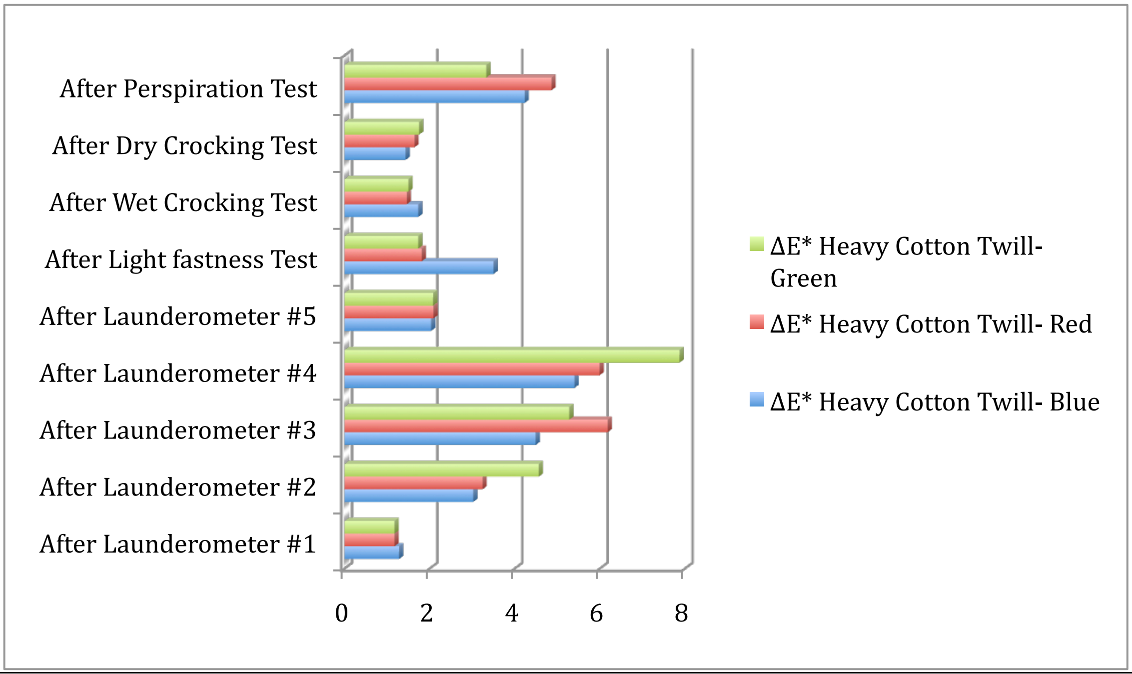

Figure A.1 ΔE* Pigment- Cotton Twill

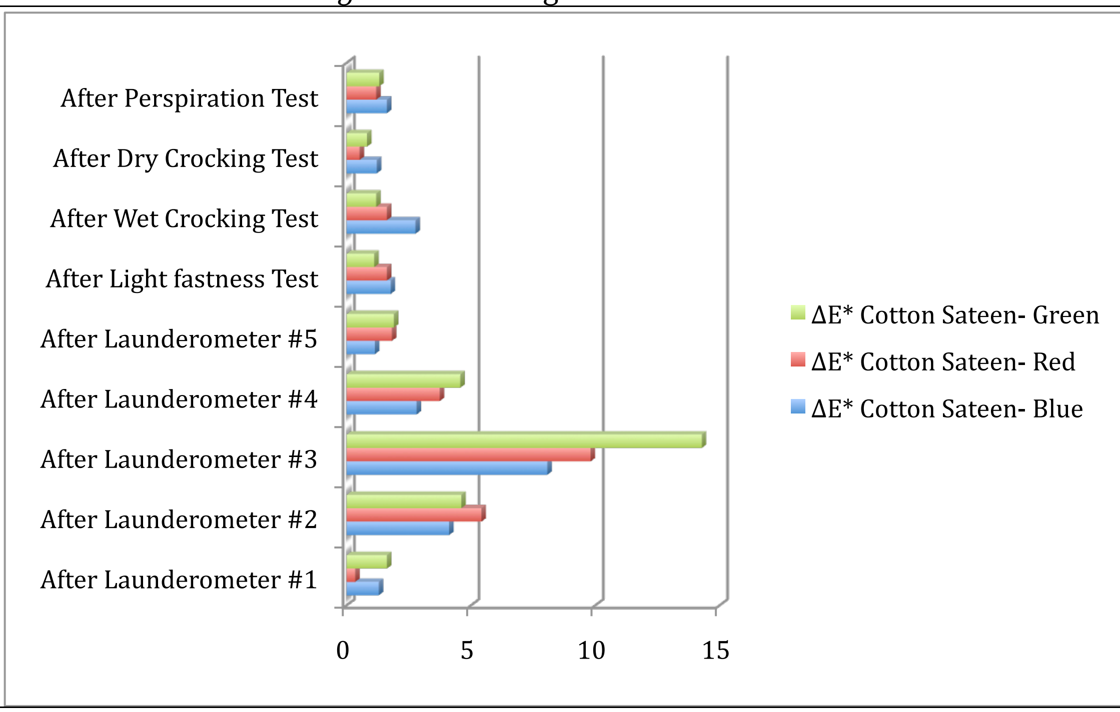

Figure A.2 ΔE* Pigment- Cotton Sateen

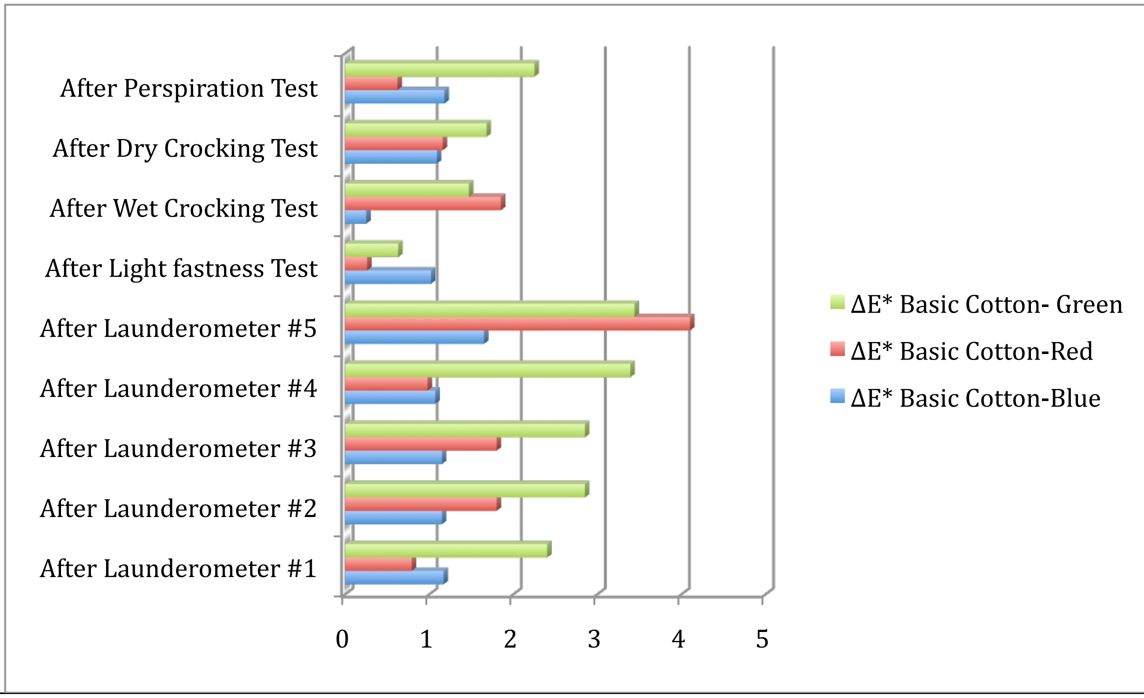

Figure A.3 ΔE* Pigment- Basic Cotton

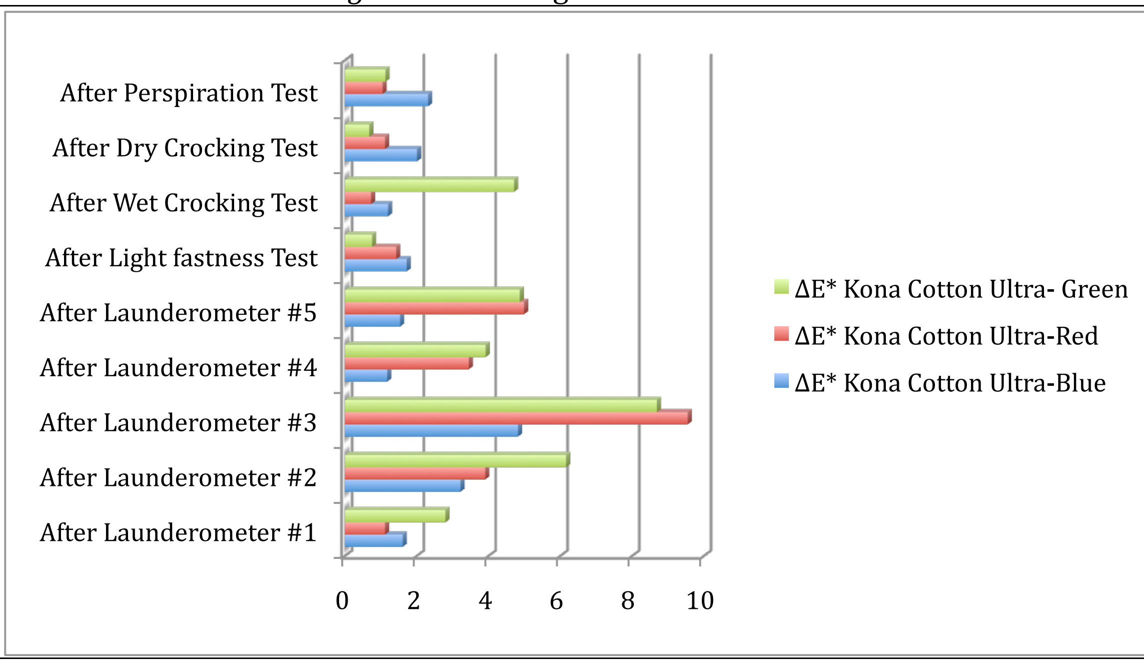

Figure A.4 ΔE* Pigment- Kona® Cotton

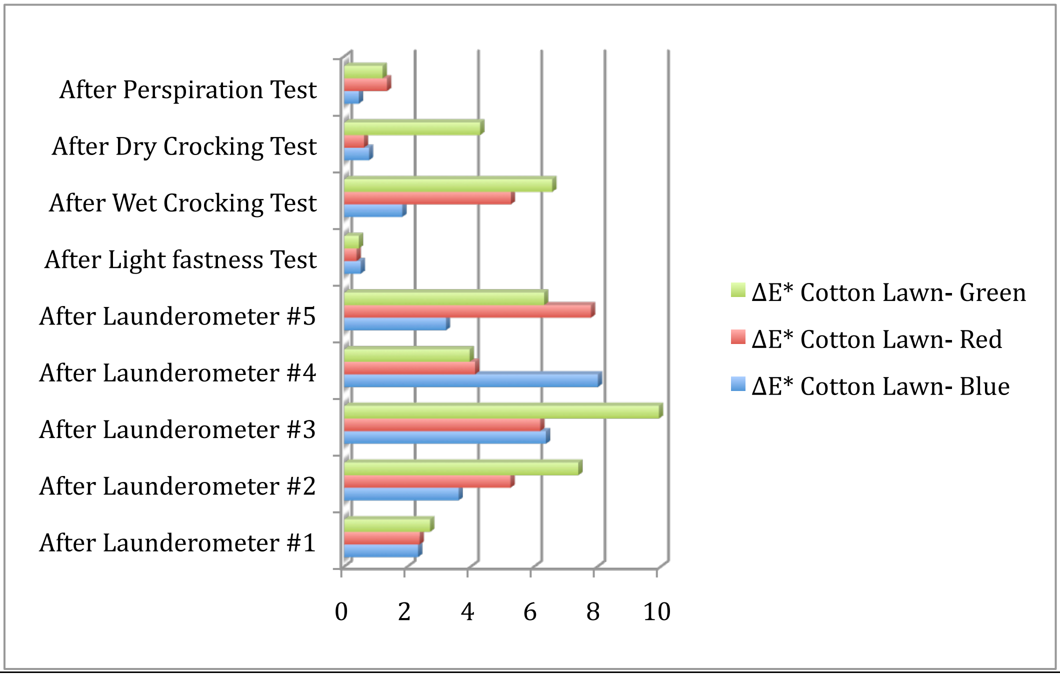

Figure A.5 ΔE* Pigment- Basic Lawn Ultra

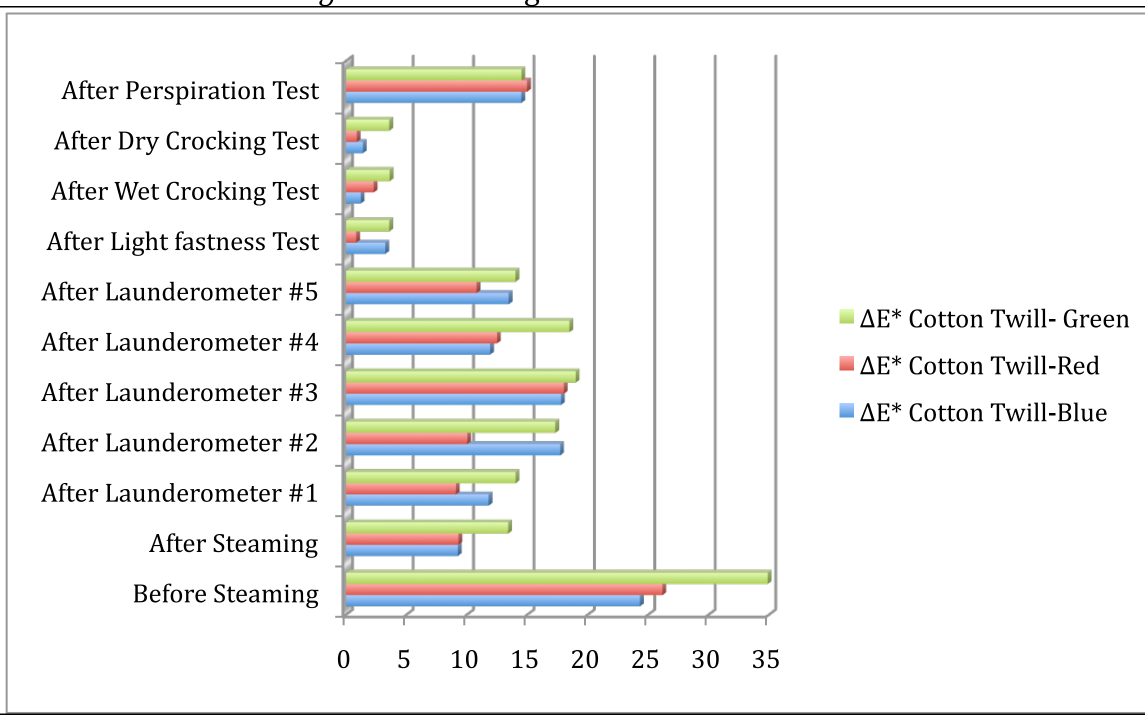

Figure A.6 ΔE* Reactive- Cotton Twill

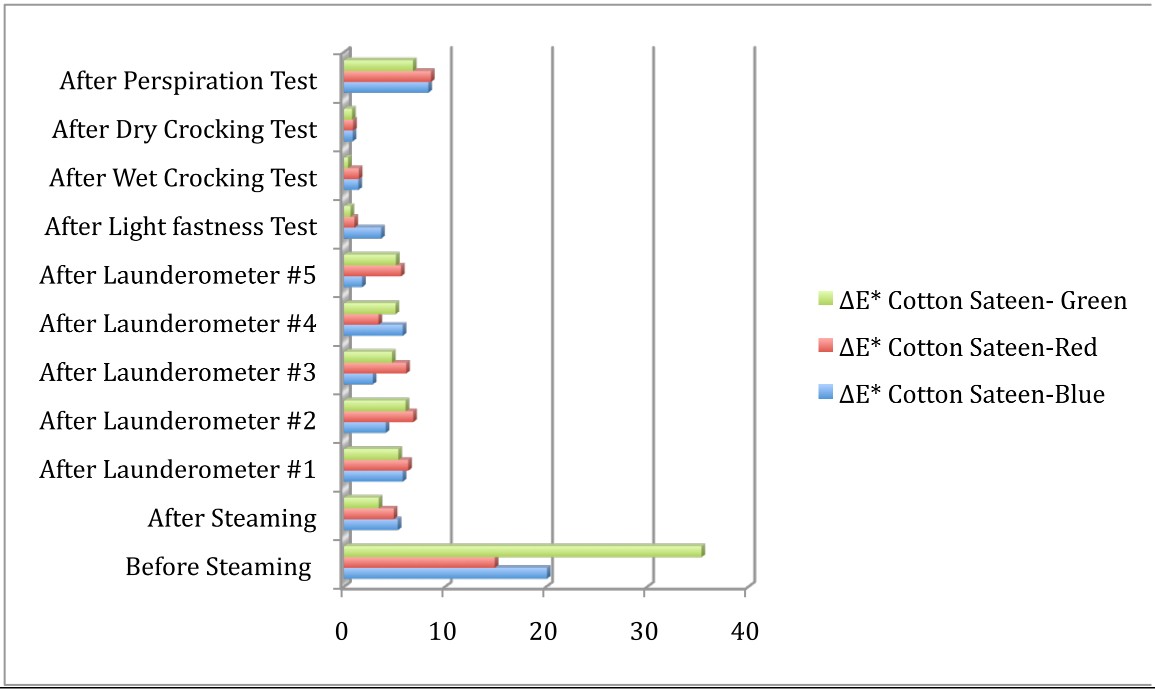

Figure A.7 ΔE* Reactive- Cotton Sateen

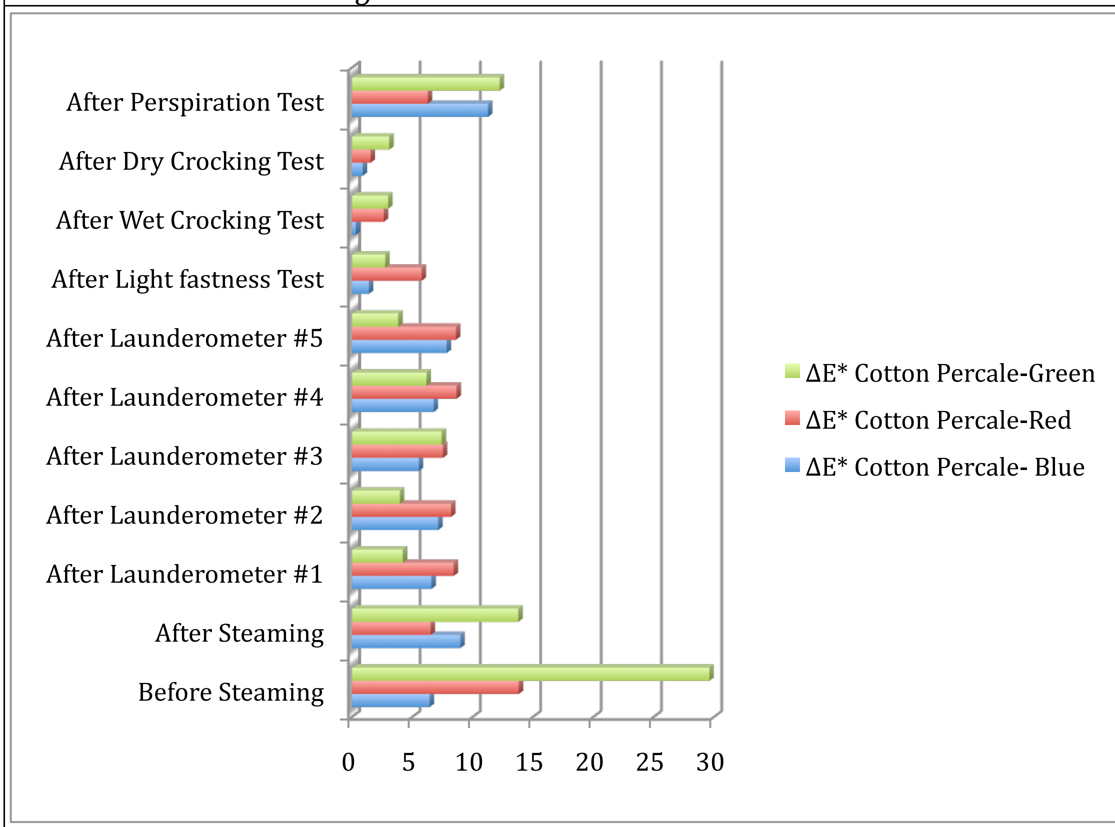

Figure A.8 ΔE* Reactive- Cotton Percale

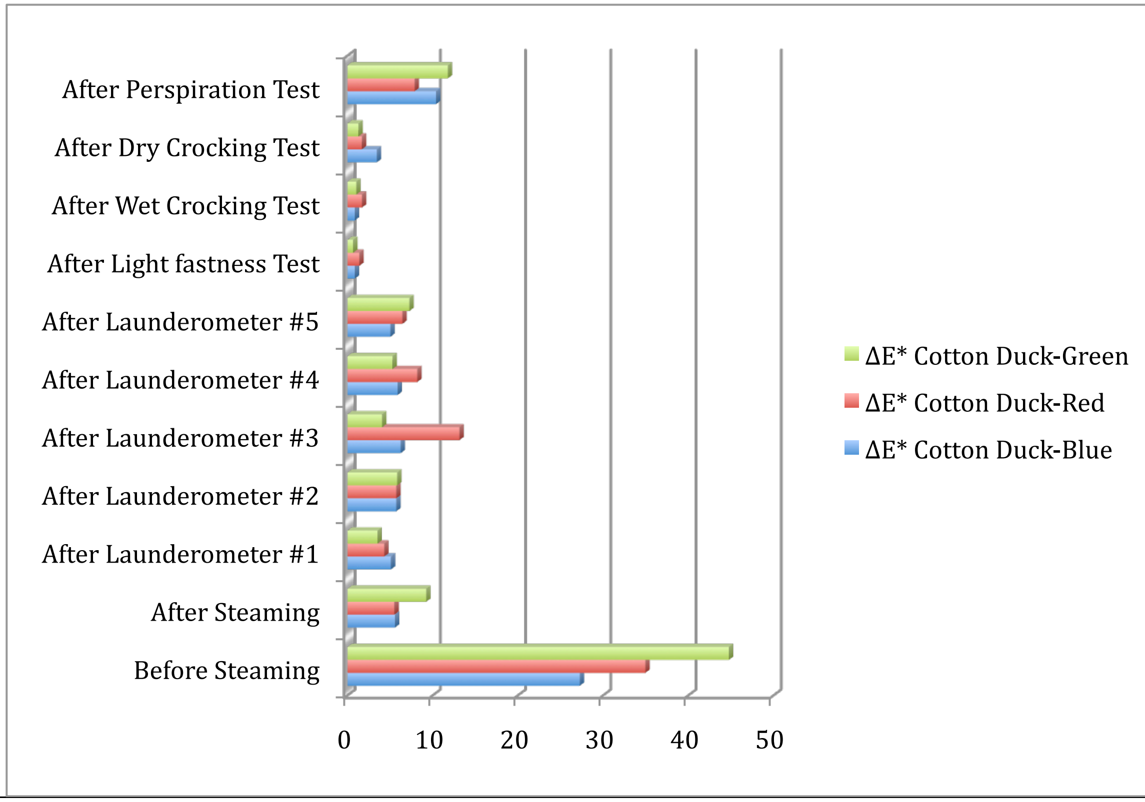

Figure A.9 ΔE* Reactive- Cotton Duck

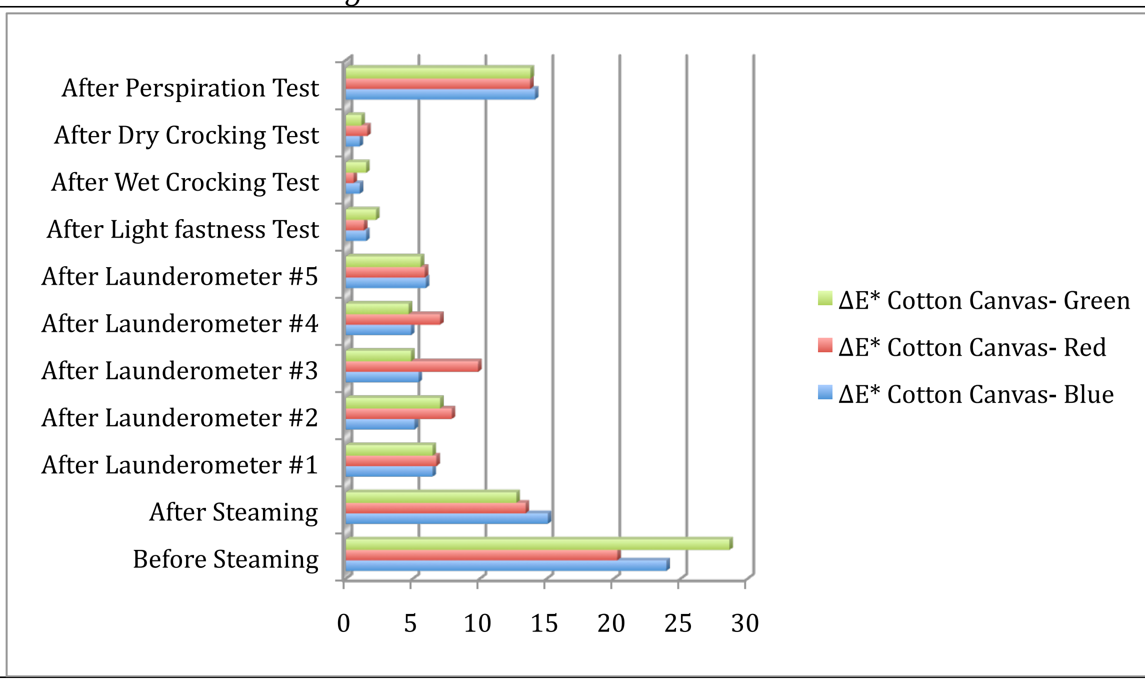

Figure A.10 ΔE* Reactive- Canvas